

SOPIA FILE

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STRATOSPHERIC OBSERVATORY  
FOR INFRARED ASTRONOMY (SOFIA)  
PHASE A  
SYSTEM CONCEPT DESCRIPTION

(NASA-TM-110669) STRATOSPHERIC  
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## FOREWORD

Infrared astronomers have made significant discoveries using the NASA/Ames Research Center C-141 Kuiper Airborne Observatory (KAO) with its 0.91-meter telescope. The need for a 3-meter class airborne observatory has been established to improve astronomy data gathering capability. The new system envisioned by NASA and the international community of astronomers will be known as the Stratospheric Observatory for Infrared Astronomy (SOFIA). The platform of choice for SOFIA is a modified Boeing 747SP.

SOFIA is viewed as a logical progression from the KAO. Potentially, a 3-meter telescope operating at the altitude achievable by the 747SP aircraft can be 11 times more sensitive than the KAO, can have 3.3 times better angular resolution, and will allow observations of compact sources in a volume of space up to 36 times that of the KAO. The KAO has enabled detection of about 15 percent of the far infrared IRAS survey point-sources; SOFIA should be able to detect them all.

This document presents the results of in-house ARC and contracted concept definition studies for SOFIA. Using the ARC-based Kuiper Airborne Observatory as a basis for both SOFIA design and operations concepts, the SOFIA system concept has been developed with a view toward demonstrating mission and technical feasibility, and preparing preliminary cost estimates. The reference concept developed is not intended to represent final design, and should be treated accordingly.

The most important products of this study, other than demonstration of system feasibility, are the understanding of system trade-offs and the development of confidence in the technology base that exists to move forward with a program leading to implementation of the Stratospheric Observatory for Infrared Astronomy (SOFIA).



## SOFIA REPORT OUTLINE

This report is organized to lead readers through the development of a design concept for the SOFIA Observatory, recognizing that these steps are not consecutive, but parallel and interactive as system issues cross the identified boundaries. The contents of each major section are identified on the initial page for that section. The Introduction/Overview section provides an executive summary of the study background, requirements, and objectives, and a top-level system concept description. Section 2 describes the science rationale and objectives, science comparison with other facilities, and science instrument overview. Section 3 addresses the top-level telescope system description, including constraints, budgets, and interfaces. Section 4 details the telescope subsystems' design concepts and analyses. Section 5 presents a description of the aircraft system, including key features, performance, and equipment accommodations. Section 6 outlines the proposed integration and test program, from subsystem to Observatory level. Section 7 describes the proposed Observatory ground support system, including facilities and equipment needed to support science investigators, the telescope and the aircraft. Section 8 addresses concepts for the SOFIA mission and science operations, both ground and flight. The report is generally in the format of annotated charts and figures, with text on the left and relevant tabular or graphic material on the right of each pair of facing pages.



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The SOFIA system concept presented in this document, including analyses and trades, concept definition and supporting activities, was developed by personnel of the Infrared Astronomy Projects Office (Code SR) (including the SOFIA Study Office and Telescope Systems Branch and their support contractors), and by Code EE (System Engineering Division) and Code OM (Science and Applications Aircraft Division) personnel, with support from Code SS (Space Science Division), all of ARC. In addition, voluntary inputs were solicited from industry with Perkin-Elmer, Kodak, Corning, Contraves and Lockheed Missiles and Space Company contributing. Other technical inputs were provided by various ground-based observatories including the Steward Observatory, which provided data to Federal Republic of Germany studies of the SOFIA telescope. Finally, data on the Boeing 747SP aircraft and its required modifications for SOFIA were obtained under contract with the Boeing Military Airplane Company, Wichita, Kansas.







## **SECTION 1**

### **INTRODUCTION/OVERVIEW**

- 1.1 Background**
- 1.2 General Requirements**
- 1.3 Study Objectives**
- 1.4 Observatory Overview**

## 1. INTRODUCTION/OVERVIEW

### 1.1 Background

The history of the concept for a large airborne IR telescope began circa 1965 when Dr. M. Bader, of the ARC Physics Branch, inaugurated NASA's assignment of an aircraft for airborne scientific research with the use of NASA's CV-990 (#711) for near-infrared observations of celestial objects. In 1969, the first flight of a 30 cm open-port telescope in ARC's Lear Jet took place; also at that time, planning started for installation of a 91 cm telescope in the CV-990, later changed to a C-141 aircraft. With the advent of the Boeing 747 in 1969, first astronomy community interest in that platform was voiced, and C. Gillespie of ARC initiated contact with Boeing while witnessing the first Boeing 747 flight at Everett, Washington. By 1972 the Kuiper Airborne Observatory (KAO) development was well along, and that year the Greenstein report was published calling for construction of a "Large Stratospheric Telescope" to be "...implemented toward the end of the decade...". In 1974, the first research flight of the KAO took place, studies began on a larger telescope in a larger aircraft, and the first NASA discussions were held with Boeing representatives who pointed out the advantages of the 747SP (Special Performance) aircraft for such a system. From 1975 to 1979 planning for a "Large Airborne Telescope" (LAT) continued at a low level while NASA/Headquarters and ARC were occupied with other projects. As KAO operations became very productive, the astronomy community recognized more and more the potential gains to be achieved with a larger telescope. By June 1980, the KAO staff had developed a conceptual summary for the LAT, and a paper, "Three Meter Telescope on a 747SP Platform" was presented at the IAU Symposium #96 in Hawaii, by R. Cameron, Chief of ARC's Medium Altitude Missions Branch. During 1980-1983, the IRAS and SIRTf projects continued to occupy attention and resources of Headquarters and ARC; with the successful 1983 IRAS mission, the need was seen for follow-up and exploitation of its IR survey observations. By 1984 momentum had rekindled for the LAT, with renewed ARC advocacy and increased interest of Headquarters program offices. An "ad hoc" advocacy group of infrared astronomers was formed, and Roger Hildebrand (U. Chicago) delivered a paper on "The Large Airborne Telescope" at the KAO's 10th anniversary symposium. Also in 1984, a report "SOFIA/Preliminary Feasibility Study" was issued for the renamed observatory concept at Headquarters request, by the KAO staff and the Scientists Support Group (now Science Consulting Group). In 1985, Drs. Keller and Pellerin at Headquarters programmed FY 86 funds for a Phase I study with Boeing Military Airplane Company on Boeing 747SP modifications for SOFIA. The study started in 1986 under the newly-formed ARC SOFIA Study Office, which also initiated the in-house Telescope System Phase A study.

### SOFIA HISTORY

- 1965-1969 FIRST USE OF NASA AIRCRAFT FOR IR ASTRONOMY (CV-990 AND LEAR JET)
- 1969 FIRST ASTRONOMY COMMUNITY INTEREST IN BOEING 747
- 1972 GREENSTEIN REPORT ON "LARGE STRATOSPHERIC TELESCOPE"
- 1974 FIRST RESEARCH FLIGHT OF KUIPER AIRBORNE OBSERVATORY (KAO)  
INITIAL STUDIES ON LARGER SYSTEM
- 1975-1979 PLANNING FOR "LARGE AIRBORNE TELESCOPE" (LAT) CONTINUES AT LOW LEVEL
- 1980 CONCEPT SUMMARY FOR LAT DEVELOPED BY KAO STAFF  
CAMERON PAPER, "THREE METER TELESCOPE ON A 747SP PLATFORM" PRESENTED
- 1983-1984 SUCCESS OF IRAS SHOWS NEED FOR FOLLOW-UP/EXPLOITATION
- 1984 "AD HOC" ADVOCACY GROUP OF IR ASTRONOMERS FORMED FOR LAT  
R. HILDEBRAND PAPER ON LAT PRESENTED  
"SOFIA PRELIMINARY FEASIBILITY STUDY" REPORT ISSUED AT HEADQUARTERS REQUEST
- 1985 HEADQUARTERS ALLOCATES FY86 FUNDING FOR AIRCRAFT MODIFICATION STUDY
- 1986 ARC ESTABLISHES SOFIA STUDY OFFICE, INITIATES PHASE A STUDIES

## General Requirements

### Aircraft Performance Requirements

The performance requirements for the SOFIA aircraft are based on NASA's experience with flying science and deployment missions on the Kuiper Airborne Observatory (KAO). For the deployment mission, this includes the capability to transport: an investigator and mission team of about 40 personnel (including flight crew(s)); cargo (including SOFIA-peculiar ground support equipment) of up to 46,520 lbs; and the SOFIA telescope system, a distance of 6,000 nautical miles with weather reserves. This assumes standard atmospheric conditions, no wind, and no drag increase due to the aircraft modification; the latter assumption is optimistic as there is liable to be a small drag penalty due to the aircraft contour changes around the (closed) cavity door. This distance is sufficient for a non-stop deployment to Australia, a preferred operating base for viewing southern declination targets.

For the science missions, a total flight duration of seven to eight hours, including 6.5 hours with telescope cavity door open at or above the preferred altitude of 41,000 feet, is a reasonable upper limit considering human factors and crew duty time limitations. The 41,000 foot level is assigned due to the IR- obscuring atmospheric telluric water vapor overburden, which is at only a 1% of its ground-level value at that altitude; the long endurance is necessary for an efficient science program (relative to operational cost). The time to climb requirement of 1/2 hour includes door opening and boundary layer control (BLC) fence deployment at altitude; an additional 1/2 - 1 hour is assumed for descent and landing, giving a total flight duration of 8 hours at most. The payload assumed for this mission is 71,805 lbs, including the cavity modification, telescope system, mission/science systems, ballast, and crew, science, and mission personnel. To achieve this endurance, the drag increase associated with the deployed BLC fence and open cavity will have to be held to approximately a 20 square foot "flat plate equivalent," which appears achievable. In addition, engines with "enhanced performance" modifications may be required to achieve the operating time at altitude requirement.

The platform (aircraft) attitude accuracy and stability requirements are important considerations in design of the telescope pointing control system and sizing the cavity to accommodate telescope motions. The requirement listed is achievable with commercial autopilots assuming the values are rms. To achieve peak-to-peak values of this magnitude would require an enhanced, but also existing autopilot.

Other aircraft requirements not shown include mission equipment and science/mission team accommodations, including cabin environmental control, safety/communications equipment, electrical power outlets, equipment and utilities mounting and routing accommodations, etc. The design and development of the cavity structural modification, including the door and BLC devices, is also the responsibility of the aircraft system provider, and is described in Section 5 of this report.

## TOP LEVEL AIRCRAFT PERFORMANCE REQUIREMENTS

### A. DEPLOYMENT MISSION

FLIGHT DURATION  
RANGE  
FOR PAYLOAD

≥ 13.5 HOURS  
≥ 6000 N.M. WITH IFR RESERVES  
≤ 125,000 LBS TOTAL

### B. SCIENCE MISSION

TIME TO CLIMB  
ENDURANCE AT ALTITUDE  
FOR PAYLOAD

≤ 30 MIN TO FL 410 (41,000 FT)  
≥ 6.5 HOURS AT FL ≥ 410  
≤ 72,000 LBS TOTAL

### C. OPERATIONAL EFFICIENCY

CAPABILITY FOR

≥ 120 SCIENCE FLIGHTS/YEAR  
≥ 6 ENGINEERING FLIGHTS/YEAR  
≥ 12 SCIENCE MAKEUP FLIGHTS/YEAR  
≥ 12 PILOT PROFICIENCY FLIGHTS/YEAR

### D. PLATFORM ATTITUDE ACCURACY/STABILITY

≤ ± 0.5° AZIMUTH (YAW) ACCURACY/STABILITY, AND ROLL/PITCH STABILITY  
AT ≥ FL 410 IN STABLE CRUISE/CLIMB CONDITIONS, WITH DOOR OPEN

### Telescope Optical System Requirements

The SOFIA Science Consulting Group has established a lower limit for the primary mirror diameter of 2.5 meters, with a goal of 3.0 meters, to provide a telescope with the greatest possible sensitivity which can fit within the cavity dimensions of a modified Boeing 747SP. Current telescope and cavity design concepts are for a 3 meter primary, which appears feasible under certain conditions. A primary f/no. of about 1.0 is required for this diameter to fit the overall telescope, including required motion range, in the cavity. System f/ratios in the range of 11-18 are needed to accommodate various science instrument requirements, with interchangeable secondary mirrors providing at least 2 f/ratios (currently 13.5 and 17) within the range, at the specified image quality. The latter is defined for optical and dynamic considerations only, for on-axis sources at 0.5 microns; the effects of seeing due to shear layer and temperature imbalance are to be added in RSS fashion for an overall image quality budget. The telescope must provide both a Cassegrain focus (behind the primary) and a Nasmyth focus (through the air bearing), with replaceable tertiary mirrors allowing use of both. Provision of the Nasmyth focus location is critical for allowing experimenter inflight access to adjust or repair the instrument package, reducing instrument development cost and allowing use of the most current instrument technology. The primary mirror must be removable to allow recoating with vapor-deposited aluminum at least semi-annually, based on KAO experience with contamination. The optics temperatures and their spatial distribution requirements are needed to minimize the effects of seeing and background variation. The optics and structure thermal time constant requirement is also established to minimize effects of thermally driven cavity seeing, and to promote efficient ground cooling operations.

## TOP-LEVEL TELESCOPE OPTICAL SYSTEM REQUIREMENTS

• PRIMARY DIAMETER	≥ 2.5 m (GOAL 3.0 m)	• PRIMARY COATING	BARE ALUMINUM, RECOATABLE ≥ TWICE/YEAR
• PRIMARY F/NO.	~ 1.0	• SYSTEM EMISSIVITY	≤ 15% AT NASMYTH FOCUS
• SPECTRAL RANGE	0.3 - 1600 MICRONS	• OPTICS TEMPERATURES	WITHIN -10 AND +2K OF CAVITY AIR TEMPERATURE
• FIELD OF VIEW	≥ 8 ARCMIN AT F/18 SYSTEM	• THERMAL TIME CONSTANT	≤ 1 HOUR (OPTICS & STRUCTURE)
• F/RATIOS	11-18 RANGE	• PRIMARY TEMP DISTRIBUTION	≤ ± 1K SPATIAL WITH PRECOOL
• IMAGE QUALITY	80% VISIBLE ENERGY IN ≤ 1.0 ARCSEC DIAMETER CIRCLE FOR CENTRAL 2M APERTURE (POINT SOURCE)	• SECONDARY MIRRORS	AT LEAST TWO, WITH SYSTEM F/RATIOS OF 13.5, 17
	80% IN ≤ 3 ARCSEC DIAMETER CIRCLE FOR ENTIRE APERTURE	• TERTIARY MIRRORS	TWO FLATS, ONE DICHROIC AND ONE REFLECTING
• CONFIGURATION	GENERIC CASSEGRAIN TELE- SCOPE, WITH CASSEGRAIN AND NASMYTH FOCI		DICHROIC TRANSMISSIVITY ≥ 70% AT 0.5 MICRONS  DICHROIC REFLECTIVITY ≥ 92% AT ≥ 10 MICRONS

### Telescope Functional Requirements

The telescope system "functional" requirements are summarized. Quiescent pointing stability (smooth flight conditions) is derived from the image quality requirements, using focal plane guidance. (Note that a boresighted fine tracker camera, mounted to the telescope metering structure, will also be available for fine tracking, but with reduced accuracy/stability over a wider field-of-view.) The cavity and door are sized for a 20-60° (above horizontal) elevation range without vignetting, and  $\pm 2^\circ$  of cross-elevation and line of sight motion range; the  $\pm 4^\circ$  goal for these motions may require telescope size reduction, and is under review. The 20-60° elevation range is important to allow viewing of a wide range of celestial objects from one base of departure, with minimal flight path or time of year constraints. Automatic telescope caging shall be provided if torque or motion range near limits (e.g., in turbulence). The telescope shall be capable of slewing at 24 arcmin/sec maximum, with additional requirements to provide nodding and scanning motions. An acquisition camera shall also be provided for initial coarse pointing, with zoom-out field of at least 9x10 degrees for stars of  $M_v \leq 11$ , and zoom-in field of 2.5x3.5 degrees for stars of  $M_v \leq 13$  (at night). It shall also provide back-up tracking capability, (or tracking for large angle offsets) with  $\leq 15$  arcsec accuracy. The secondary mirror(s) shall provide "reactionless" chopping motions as shown, plus the capability to perform adjustable and dithering focusing motions. Auxiliary secondary mirror motion controls are to be provided at the experimenter control panel. Additional requirements for science instrument accommodations, cavity provisions, mission equipment/cargo accommodations, safety provisions, ground support, etc., are provided in project document PD-2000, "SOFIA and Related Requirements", which also gives greater details of the above summarized system requirements.

### TELESCOPE SYSTEM FUNCTIONAL REQUIREMENTS SUMMARY

• POINTING STABILITY (QUIESCENT)	≤ 0.15 ARCSEC RMS (LONG-TERM JITTER)	• TARGET ACQUISITION	TIME TO ACQUIRE INVISIBLE TARGET ≤ 30 SECONDS
	≤ 1.0 ARCSEC RMS (OFFSET GUIDING)		DEAD RECKONING ACCURACY ≤ 15 ARCMIN
• TELESCOPE MOTIONS	ELEVATION RANGE 20-60° UNVIGNETTED 15-75° VIGNETTED	• INERTIAL REFERENCE	CAPABILITY FOR AUTOMATIC OFFSETS (STAR TO STAR)
	CROSS ELEVATION AND LOS RANGE ±2° (4° GOAL)		DRIFT RATE ≤ 0.5 ARCSEC/SEC (GYRO-ONLY CONTROL)
	AUTOMATIC CAGING CAPABILITY	• SECONDARY MIRROR	FUNCTIONS: CHOP, ROTATE, FOCUS, FOCUS DITHER
• SLEW/NOD/SCAN	≥ 0.4 DEGREES/SEC MAX SLEW RATE		CHOP AMPLITUDE: 2 ARCSEC - 8 ARCMIN (OBJECT SPACE)
	NOD AMPLITUDE ≥ 20 ARCMIN		CHOP WAVEFORMS: SQUARE, SAWTOOTH, ARBITRARY, OFFSET
	NOD/SETTLE ≤ 2 SEC, FOR 5 ARCMIN AMPLITUDE		CHOP END POSITION STABILITY ≤ 1% OF AMPLITUDE
	MAPPING PATTERNS: CIRCULAR, SPIRAL, RECTANGULAR PATTERNS		CHOP RISE TIME ≤ 5 MSEC FOR 1 ARCMIN AMPLITUDE ≤ 7 MSEC FOR 4 ARCMIN AMPLITUDE
• OFFSET POINTING (FOCAL PLANE TRACKING)	RANGE ≥ 8 ARCMIN DIAMETER AT NASMYTH FOCUS		CHOP FREQUENCY 1-35 Hz (1 ARCMIN) 1-10 Hz (4 ARCMIN)
	ACCURACY ≤ 1 ARCSEC		
	RESOLUTION ≤ 0.15 ARCSEC		
	SENSITIVITY: TRACK ON STAR OF $m_v \geq 13$		

### Study Objectives

The overall objectives of the in-house SOFIA Phase A Telescope System study were to establish feasibility of achieving the performance requirements within established system constraints (e.g., size, mass); and to develop a preliminary Telescope System cost estimate. Concurrently, a contracted effort with the same objectives was performed by Boeing Military Airplane Company (BMAC) for the aircraft system, with major emphasis on the cavity modification. The results of the BMAC study are fed back to the Telescope System to establish system constraints and define interfaces.

In order to achieve the Telescope System study objectives several steps were required. First, a review of the system performance requirements as established by the Science Consulting Group (SCG) was performed, including a flowdown of requirements and error budgeting exercise to establish subsystem requirements/constraints and boundaries. Next, subsystem conceptual designs were developed using the KAO configuration and existing technology where available and applicable, including alternate approaches if warranted. Detailed technical analyses, including model development, calculations and computer simulations, were then performed to determine performance capabilities of the candidate concepts, and to establish feasibility of meeting the requirements/constraints with the candidate designs. In cases where required performance was obviously not achievable, alternate design approaches were chosen with iteration of the analyses. Having established the "final" preliminary concepts, technology drivers and areas of concern were identified, where, for example, performance shortfalls still existed, sufficient information or modeling was not available, or further analysis was needed. The subsystem concepts were then integrated and reported out, in formats usable to establish preliminary system cost estimates, employing, for example, mass and complexity factors as cost model entering parameters. Cost estimates were then developed using various techniques and models (e.g., grass-roots, "RCA PRICE"), and uncertainties or ranges were factored in. A final systems engineering function was to define interfaces, assess the various concerns and uncertainties, and develop costs of alternative approaches. The risk assessment is to be used in an effort with Project Management to report back a "Project Position" on alternate system performance requirements (where necessary), which are felt to be achievable with acceptable risk. These will be iterated with the SCG to develop updated performance requirements for future project phases.

## STUDY OBJECTIVES

- DEVELOP KEY SUBORDINATE SUBSYSTEM REQUIREMENTS AND ERROR BUDGETS FROM TOP-LEVEL PERFORMANCE REQUIREMENTS (REQUIREMENT FLOWDOWN AND ERROR BUDGETING)
- DEVELOP BASELINE SYSTEM AND SUBSYSTEM CONCEPTS (AND OPTIONS) USING KAO AND EXISTING TECHNOLOGY AS STARTING POINT
- PERFORM DETAILED TECHNICAL ANALYSES TO ESTABLISH FEASIBILITY OF ACHIEVING PERFORMANCE REQUIREMENTS WITHIN GIVEN SYSTEM CONSTRAINTS, USING PRELIMINARY CONCEPTS
- ITERATE DESIGN CONCEPTS/DEVELOP DIFFERENT APPROACHES AS NECESSARY
- IDENTIFY TECHNOLOGY DRIVERS AND AREAS OF UNCERTAINTY OR CONCERN, REQUIRING EARLY FOLLOW-ON EMPHASIS TO RESOLVE
- REPORT ON CONCEPTS, INCLUDING MASS/COMPLEXITY FACTORS TO ENTER COST MODELS
- ESTABLISH PRELIMINARY COST ESTIMATES, INCLUDING COST RANGE DUE TO UNCERTAINTIES
- DEFINE KEY SUBSYSTEM AND SYSTEM INTERFACES
- ESTABLISH "PROJECT POSITION" RELATIVE TO REQUIREMENTS ACHIEVABILITY, AND SUGGESTED CHANGES TO PERFORMANCE REQUIREMENTS WHERE WARRANTED

## **Observatory Overview**

### **Major Elements**

This section provides a top-level description of the SOFIA Observatory concept, as developed through in-house Phase A studies at ARC and contracted Phase A studies by Boeing Military Airplane Company (BMAC). Detailed technical descriptions are provided in Section 3 (Telescope System), Section 4 (Telescope Subsystems), Section 5 (Aircraft System), and Section 7 (Ground Support System).

For purposes of this overview description of the Observatory, the SOFIA concept is conveniently divided into the Aircraft System, Telescope System, and Ground Support/Operations System, which are briefly described in that order in the following pages. The Aircraft System consists of the basic aircraft, the cavity modification including door and Boundary Layer Control devices, and aircraft accommodations for the telescope, mission equipment and crew. The Telescope System encompasses the Telescope Assembly (optical subsystem, supporting structure, instrument mount/counterweight, and air bearing/vibration isolation system), and the Consoles and Electronics subsystem. Finally, the Ground Support/Operations System includes ground facilities, resources and equipment needed to support the aircraft, telescope, science instruments and investigators, and flight operations.

## **SOFIA OBSERVATORY CONCEPT OVERVIEW MAJOR ELEMENTS**

- AIRCRAFT SYSTEM
  - BASIC AIRCRAFT, CAVITY MODIFICATION, AND EQUIPMENT AND CREW ACCOMMODATIONS
- TELESCOPE SYSTEM
  - TELESCOPE ASSEMBLY: OPTICAL SUBSYSTEM, SUPPORT STRUCTURE, COUNTERWEIGHT/INSTRUMENT MOUNT, STRUCTURAL ISOLATION
  - CONSOLES AND ELECTRONICS SUBSYSTEM: PROCESSORS, CONTROLS AND DISPLAYS FOR TELESCOPE OPERATIONS, MISSION MANAGEMENT, AND SCIENCE INVESTIGATION
- GROUND SUPPORT/OPERATIONS SYSTEM
  - GROUND FACILITIES, RESOURCES AND EQUIPMENT FOR TELESCOPE, AIRCRAFT, INSTRUMENT/INVESTIGATOR, AND OPERATIONS SUPPORT

### Aircraft System Overview

The accompanying "Layout for Personnel Accommodations" (LOPA) was developed as part of a BMAC Phase A contracted study, using a Boeing 747SP (Special Performance) aircraft as the baseline SOFIA platform. The high-altitude/long endurance capabilities of this model, combined with its large cabin cross-section, make it the aircraft of choice to fulfill the SOFIA requirements. No other existing aircraft can rival this combination of attributes.

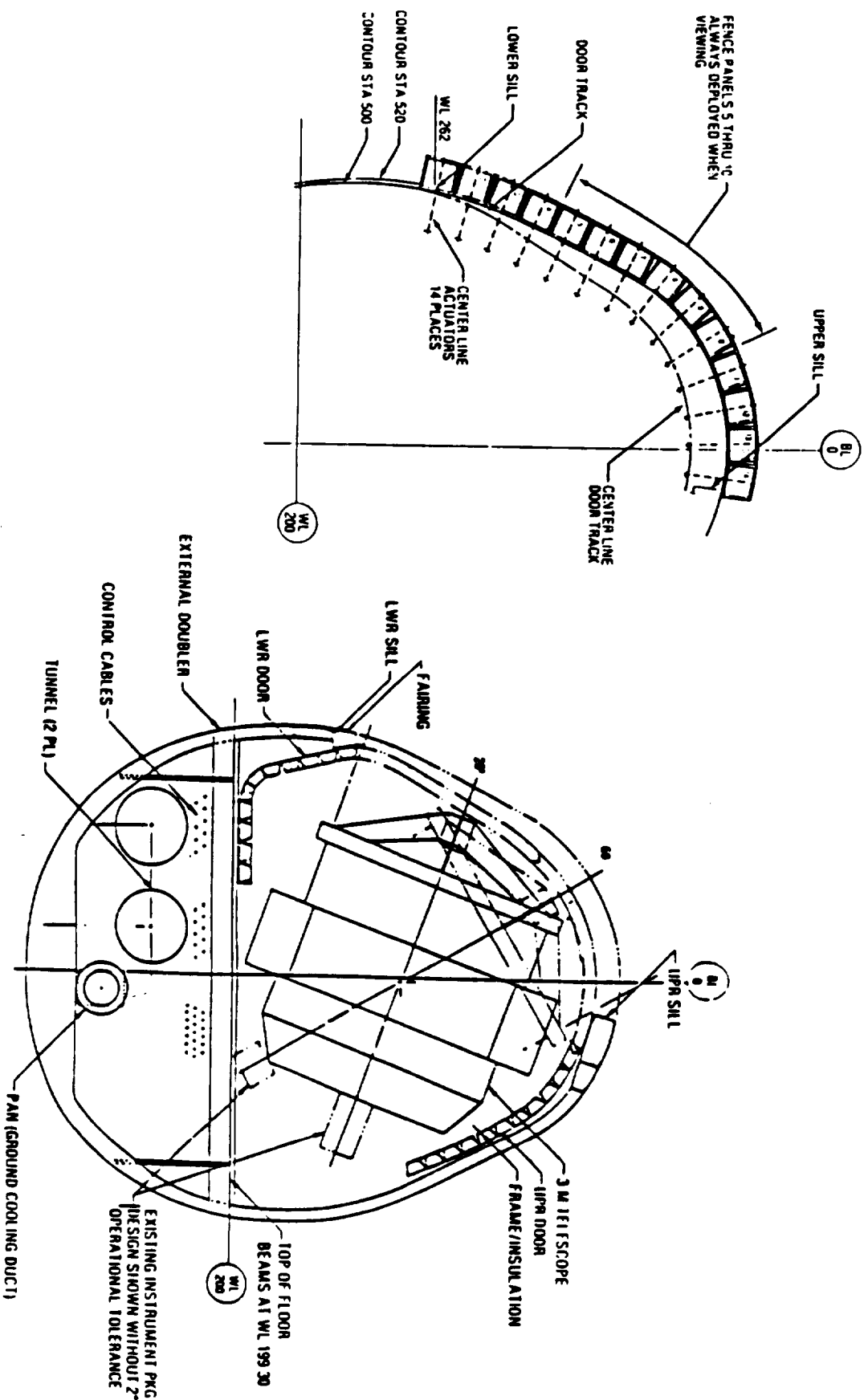
The LOPA depicts the configuration of the entire aircraft, telescope, and mission systems; larger drawing versions can be obtained from ARC on request. (A clearer three-page version is included in Section 5.) Main features include two full-depth pressure bulkheads forward of the wing, which isolate the cavity/cabin environments; the aft bulkhead mounts the telescope vibration isolators which support the entire air bearing/telescope/counterweight; the forward bulkhead contains an access door and telescope caging device. Two pressurized transfer tunnels pass beneath the telescope for personnel fore-aft transfer and systems routing (e.g., ducts, wiring, etc). Due to aircraft center of gravity constraints and cavity generated noise, all mission/science personnel and equipment are located in the aft section, behind a sound insulating partition; however, one science investigator console is located adjacent to the instrument/counterweight area, to provide instrument access and monitoring. Other aft mounted equipment includes air compressors (for the air bearing and vibration isolators) and liquid nitrogen tanks (for cavity precool/dehumidification). Standard aft-mounted galleys and lavatories, and the aft cargo compartment remain basically unchanged from the commercial aircraft. Aircraft power is distributed to all users from a panel located in front of the sound partition. The entire science mission payload is estimated to weigh just under 72,000 lbs, including ballast.



### Cavity Concept

The diagram illustrates a 3.0 meter (primary mirror diameter) SOFIA telescope as it would be located in the cavity conceptualized by BMAC. The two telescope elevation extremes - 20° and 60° above horizontal - are shown; as can be seen, clearances are not generous. This cavity uses the existing floor location and outer skin configuration; cost would increase significantly to modify these geometries. The two-section, segmented cavity door is shown fully open at top and bottom; during operation, it would be open just enough to preclude telescope vignetting and would follow telescope elevation motion. Likewise, the BLC fence (shown separately), which protrudes in an arc outside and forward of the open port, will be segmented with separate actuators to allow telescope "following". Both of these provisions are needed to minimize drag, which impacts aircraft altitude and endurance capability. The open port extends past the aircraft centerline at top, and requires major structural strengthening, using skin doublers. Below the floor are depicted the two pressurized transfer tunnels, and the ground cooling system duct which runs from the cavity to the aircraft underbelly exterior. Aircraft control cables are also rerouted under the floor. This view is looking forward at the center of the telescope location in the cavity.

## CAVITY CONCEPT - REAR VIEW AT TELESCOPE CENTERLINE



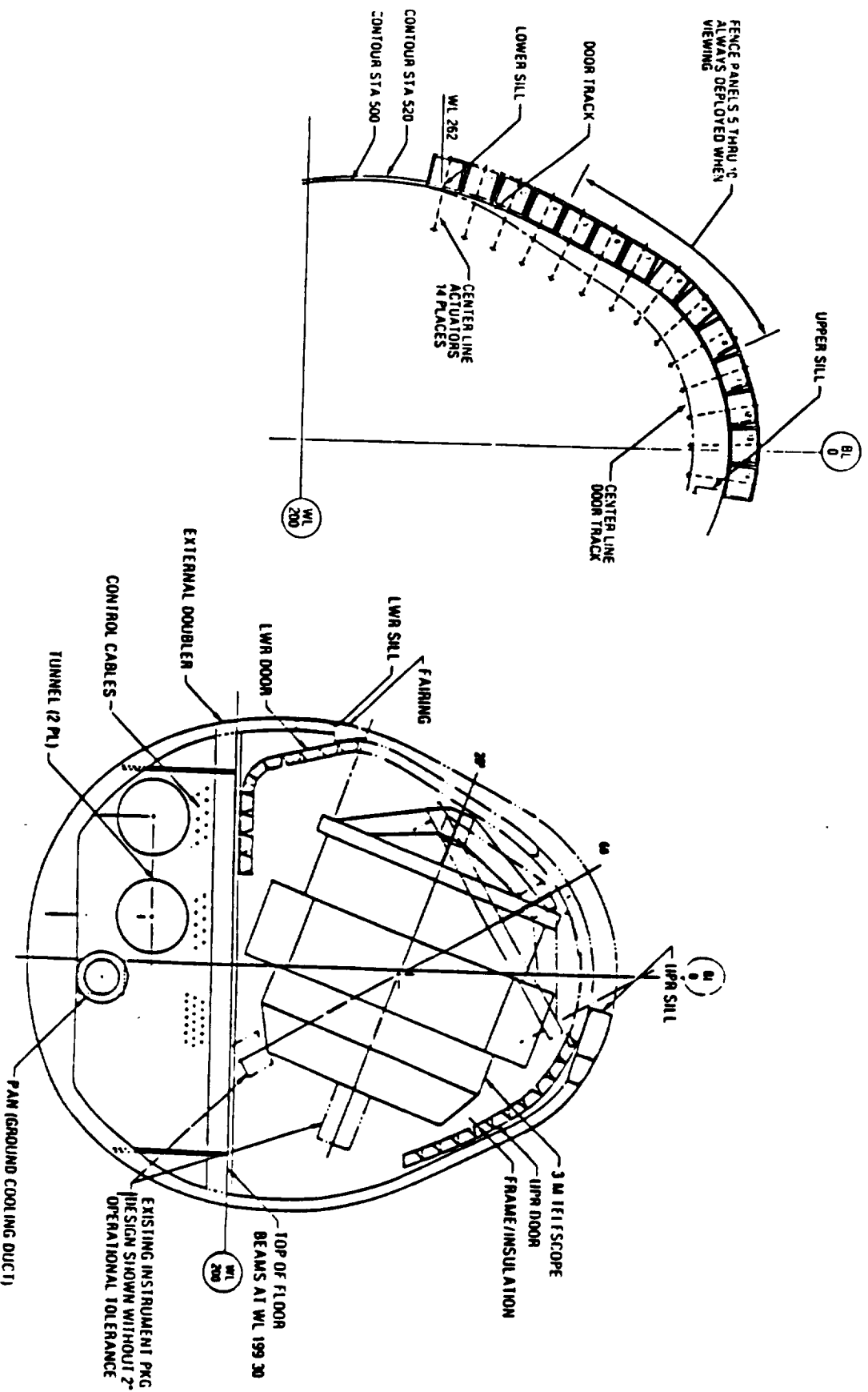
## Telescope System Overview

### Structure

The major structural components of the telescope system concept are shown. The structure must support the telescope optical components (mirrors) allowing minimal relative deflections under various loading and thermal conditions; allowable deflections, which include bending across the airbearing/support tubes, have been budgeted for structural design. Another major constraint is the system mass, where a goal of 30,000 lbs maximum (including air bearing and vibration isolation system) has been established. The structure must be large enough to support the 3 meter primary, while being sufficiently compact to fit within the aircraft cavity, considering all motions. Finally, the lowest natural frequency must be high enough to avoid resonance and control problems.

The basic structure features an optimized centerpiece which, due to its complex geometry and fabrication requirements, is baselined as 1/2 inch aluminum plate. A graphite-epoxy/aluminum sandwich cylindrical metering tube is envisioned, although a Serrurier strut arrangement is also viable. The heading/spider assembly provides stiff mounting for the chopping secondary mirror. Invar support tubes connect the telescope centerpiece to the airbearing rotor, and the rotor to the instrument flange/counterweight assembly, located in the aircraft cabin. The counterweight design has not been optimized; it is likely that a longer, narrower geometry will be preferable to minimize weight while balancing moments about the air bearing centerline. The bottom of the telescope is a removable "tub" which contains the primary mirror support system holding the mirror; the mirror must be recoated periodically in a separate facility. Likewise, the headinging is removable to allow interchange of secondary mirrors.

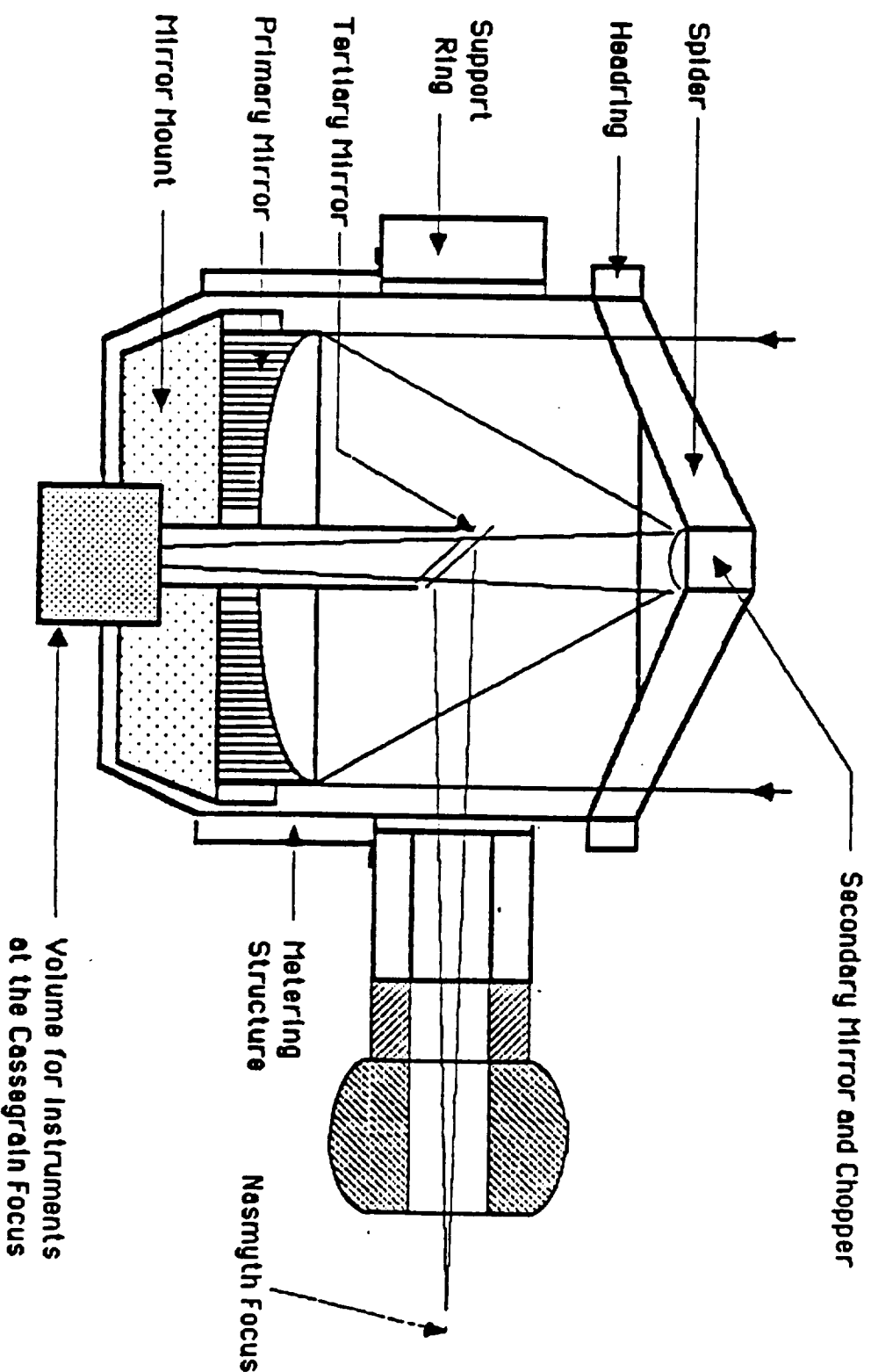
## CAVITY CONCEPT - REAR VIEW AT TELESCOPE CENTERLINE



### Optical Configuration

The Telescope System optical layout is depicted, consisting of a "generic" Cassegrain configuration with provisions for instruments at the Cassegrain focus and Nasmyth focus. The latter is accommodated by use of a removable tertiary flat mirror which reflects the beam 90° aft through the air bearing. A possible arrangement uses two tertiaries, the first dichroic to reflect the infrared beam while passing visible light to the second, which reflects to an offset fine guidance sensor mounted near the focal plane. Options for the exact optical form include a classical Cassegrain, a Ritchey-Chretien, and conceivably a "coma-compensated" design. The approximately f/1, 3-meter primary options include a frit-bonded "Ultra-Low Expansion" (ULE) quartz mirror (chosen for this study), a thin meniscus Zerodur design, or a spin-cast borosilicate design. The mirror is to be coated with vapor-deposition aluminum. The chopping secondary mirror concept is a "reactionless" design to minimize chopping vibrations imparted to the structure. Interchangeable secondary mirrors provide an f/11 Cassegrain focus, and f/13.5 and f/17 Nasmyth foci. Although a stationary tertiary is envisioned, an option requiring further evaluation is an active tertiary providing image motion compensation to the Nasmyth focal plane. Not shown are various sensors and devices needed for telescope operation, including inertial reference units (gyros), barrel-mounted acquisition and tracker cameras, primary mirror blower, primary mirror mount details, etc. These are described in later sections.

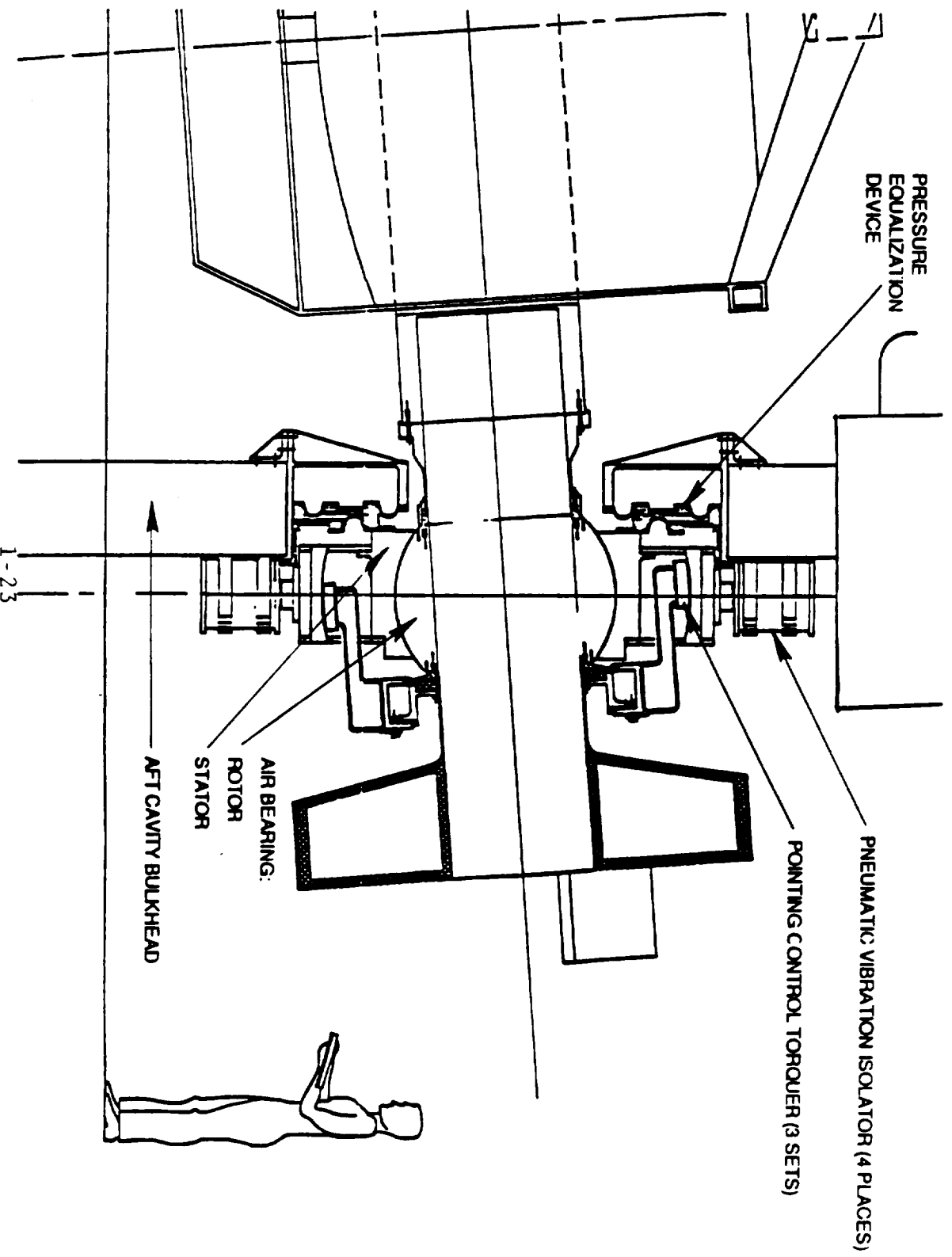
## TELESCOPE CONFIGURATION



### Telescope Support

The concept for supporting the SOFIA Telescope/counterweight is very similar to the successful KAO design, although scaled up to handle the increased size and mass. The three major elements shown are the air bearing, vibration isolation actuators, and telescope motion torquers. The air bearing is intended to provide a near-frictionless, three-axis rotating mount which accommodates unlimited elevation (aircraft roll axis) motion, and plus or minus 5° of "cross elevation" motions (pitch/yaw). It must also have at least a 31 inch "light path" inner diameter, accommodate the cabin/cavity pressure and temperature differentials, and preclude warm, compressed air from entering the cavity (with a scavenging system). A pressure seal system, which equalizes pressure on both sides of the bearing, is shown on the cavity side of the air bearing stator. Electromagnetic torquers are shown just outside of the air bearing; three sets of these in different locations provide the required 3-axis torquing used for target tracking, nodding, scanning, and slewing motions, plus field-rotation compensation. The vibration isolation system mount also uses compressed air, which is modulated to attenuate aircraft structure-borne vibration into the Telescope System. These pneumatic pistons are shown at top and bottom mounted to the aft cavity bulkhead; two more are located at each side of the air bearing in the current concept.

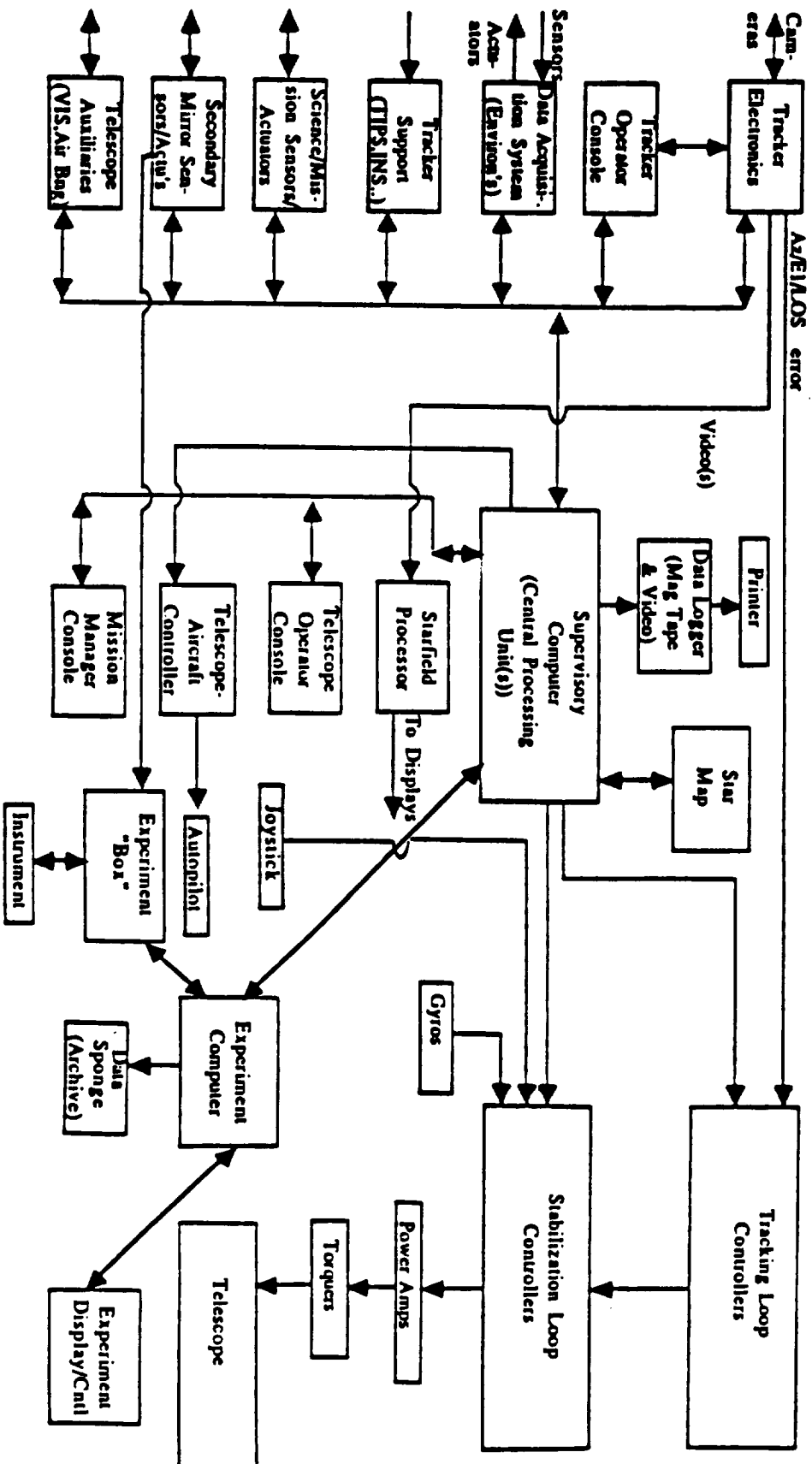
## TELESCOPE SUPPORT SYSTEM



### Telescope System Communications

The top-level communications block diagram depicts the interactions required amongst numerous mission and science operations elements; the system is similar to the KAO. On the left side are all the support sensors and actuators (except Telescope torquers) required for mission/science operation. The "cameras" include acquisition and tracking sensors, whose fields are displayed at the tracker operator console; the latter has a joystick for manual tracking, slewing, nodding, etc. Environmental "sensors" include cavity/telescope temperature, cavity dewpoint, pressure transducers, hygrometers, air data sensors, accelerometers, etc; "actuators" include primary mirror "blower," cavity heating/cooling controllers, compressors, etc. "Tracker support" sensors include telescope/cavity relative position sensors (TIPS), Aircraft inertial navigation system (INS) attitude sensors, etc. Science/mission sensors include boundary layer control (BLC) fence positions, cavity door positions, instrument dewar cryogen level, instrument filter selection, etc.; "actuators" control these same devices. A central processor unit (redundant) is the central communications node and supervisory computer, linking peripheral devices and operator consoles via a local area network. The telescope pointing control system includes the cameras and inertial sensors (gyros), with links to TIPS and the aircraft INS; it integrates "error" inputs and joystick commands, into the tracking and stabilization loop controllers, and feeds the resulting pointing commands to the telescope torquers. The various manned consoles include: the tracker operator console, with a starfield display, joystick, keyboard and "mouse"; telescope operator/monitor console with a tracker (repeater) display, system status display and keyboard/mouse; mission manager console with a mission management display and system status repeater display, and keyboard/mouse; and the investigator consoles (main and remote) with a support computer, displays (e.g., tracker, experiment status, chopper), and keyboard/mouse controls.

## TELESCOPE SYSTEM COMMUNICATIONS BLOCK DIAGRAM



### Telescope System Communications (Contd)

The SOFIA DMAC Subsystem is the Observatory data management, acquisition and communications network, with the design concept based on the KAO (with planned upgrades). Major requirements for the data/command system include: high reliability, with high mean time between failures and high noise immunity; redundancy, including a backup data central processor unit (CPU) available for immediate switchover, with stand-alone and network operation; modifiability/ expandability, including standardization of hardware and communication protocols in a network concept; and communications requirements, with direct subsystem-to-subsystem data communication via a local area network (LAN - industry standard), network manager and test work station for network configuring and system maintenance, and capability for a hardwire (on-ground) link to ground based system simulators to increase efficiency of user integration. The design approach divides the SOFIA system into major subsystems, such as the secondary mirror, data CPU, telescope support systems, etc., and interconnects these subsystems through the broadband LAN. Each of the major subsystems consists of from one to seven elements, including the LAN interface, control unit, control panel/terminal, operating system, personal computer, drive electronics/motors, and diagnostic software, which are subsystem dependent. Proven/existing technology, hardware, software, and standardized systems are to be used as much as possible to reduce system complexity, maintenance, and cost, and to enhance expandability.

## DATA MANAGEMENT, ACQUISITION AND COMMUNICATIONS SUBSYSTEM

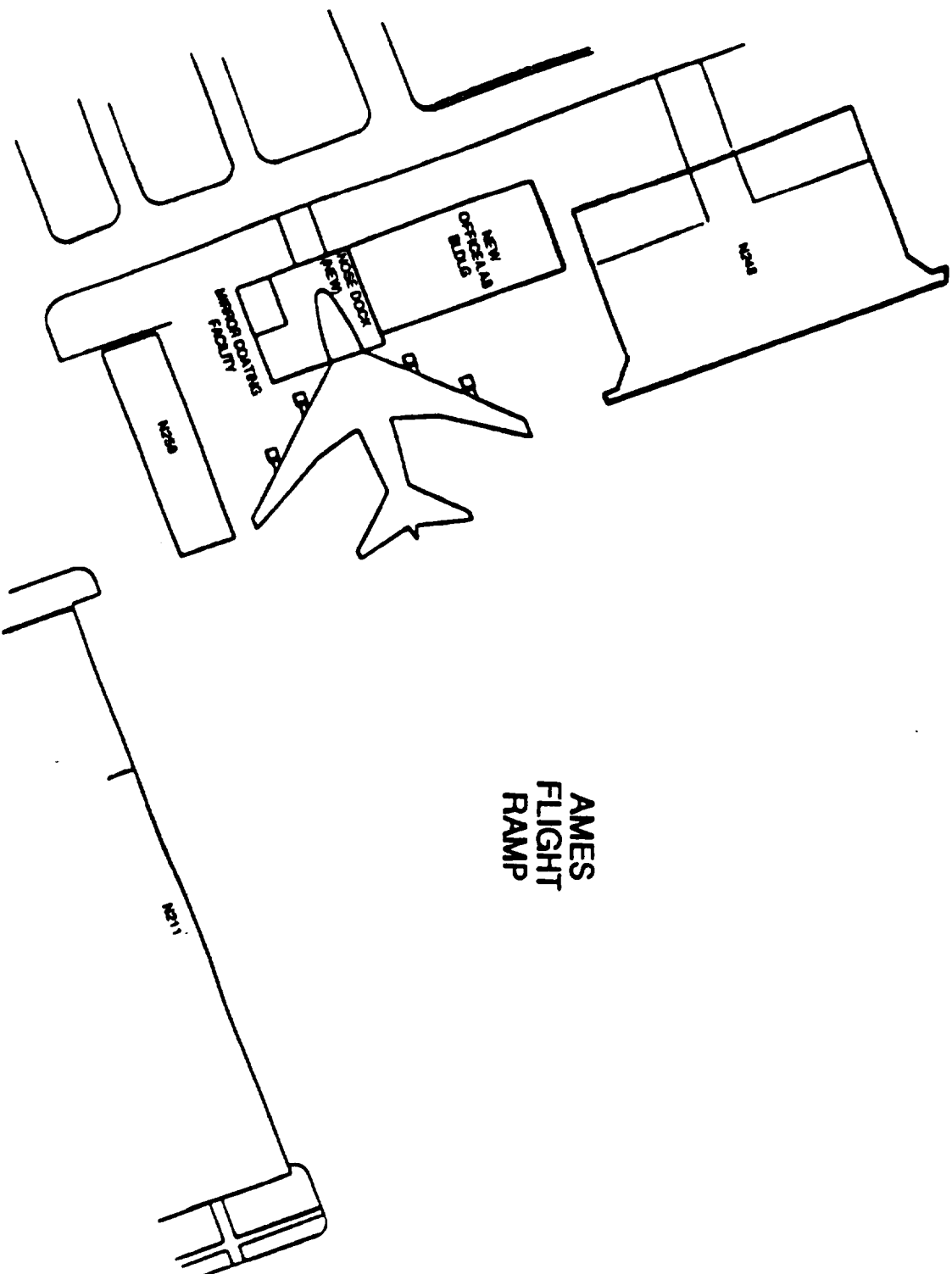
- MAJOR REQUIREMENTS
  - RELIABILITY/REDUNDANCY
  - MODIFIABILITY
  - COMMUNICATIONS (DATA AND VOICE)
  - BASED ON KAO WITH UPGRADES
- CONCEPT
  - DIVISION INTO MAJOR SUBSYSTEMS
  - INTERCONNECTION THROUGH A LAN
  - MAJOR SUBSYSTEM IDENTIFICATION:
    - SECONDARY MIRROR ASSEMBLY
    - OFFSET GUIDER (FOCAL PLANE)
    - STAR TRACKER/ACQUISITION CAMERAS
    - TELESCOPE INERTIAL POINTING (TIPS)
    - VIBRATION ISOLATION
    - TELESCOPE SUPPORT (FENCE, DOOR, ETC.)
    - INVESTIGATOR SUBSYSTEM/CONSOLES
    - HOUSEKEEPING AND DATA ACQUISITION
- DATA CPU (WITH BACKUP)
- VIDEO SIGNAL PROCESSING
- MISSION MANAGER
- NETWORK MANAGE/TEST WORK STATION
- CAVITY ENVIRONMENT
- BROADBAND LAN
- VIDEO DISTRIBUTION
- MISCELLANEOUS PERIPHERAL EQUIPMENT

## Ground Support/Operations System

### Ground Support Overview

The SOFIA Ground Support/Operations System element consists of the ground facilities, equipment, and personnel required to: operate and maintain the SOFIA aircraft; maintain, recondition and operate the Telescope System; select and schedule science investigations; support science teams and instruments at ARC; and plan and execute airborne science, and other missions. The figure depicts the support facilities concept for the Boeing 747 SP and Telescope System. Facilities required include: a "Nose-dock" hangar with access taxiway stressed for 800,000 lbs. and tow truck; mirror coating facility and equipment for Telescope optics removal/reinstallation and ground support (e.g., jigs, fixtures, cranes); ground-based cavity environmental control equipment; computer equipment for mission planning and science investigator/instrument support; SOFIA telescope simulator for instrument interface verification, and other assembly/test support equipment; miscellaneous aircraft and telescope maintenance equipment; offices for civil service, support contractor, and science investigator personnel (including navigation, flight planning and star chart room and astronomy reference library); storage facilities and investigator hygiene and rest accommodations; life support equipment maintenance and storage shop; and conference/briefing room(s). These facilities will be housed in the new buildings shown adjacent to the ARC flight ramp; space has been reserved for their construction, which will take place in the 1990-92 timeframe.

### GROUND SUPPORT FACILITY LOCATION



## Ground Support/Operations System

### Operations Overview

The SOFIA Observatory will be operated by NASA as a national facility with international collaboration and science investigations. The facility design is intended to provide compatibility with instruments/investigations developed for the KAO and, insofar as possible, with ground-based telescopes. State of the art facilities with adequate technical support staff are envisioned to provide a "user friendly" service, with considerations for human engineering (comfort, environment) for long duration observing flights. High operational reliability is required of the design to achieve yearly observation goals. The facility will be self-contained (with ground support equipment transportability) to provide operations from remote bases.

Operational goals for SOFIA include a 20-year useful lifetime with 120 research flights per year over a 40 week period. The remainder is to be used for telescope and aircraft maintenance, system modifications, pilot training and proficiency, and contingency time for make-up flights. Support service contractor staffing will handle day-to-day operations to the extent possible. A nine-month development/shake-down period is envisioned after system delivery before full operational capability is achieved, starting in FY 1992.

The research program involves science selection, observer funding and observatory scheduling during the operational period of each year. A formal science selection process will be carried out, starting with a "dear colleague" letter, submission of letters of intent and proposals, peer review and selection of investigations, and award announcements. Funding of U. S. Observers, who must submit cost plans, is by NASA grant through the ARC University Affairs Branch.

## **GROUND SUPPORT/OPERATIONS SYSTEM OPERATIONS OVERVIEW**

- **PHILOSOPHY:**
  - NASA-OPERATED WITH INTERNATIONAL COLLABORATION/INVESTIGATIONS
  - INSTRUMENT/INVESTIGATION COMPATIBILITY WITH KAO AND GROUND-BASED IR
  - USER-FRIENDLY AND "HUMAN ENGINEERED" FOR LONG-DURATION OBSERVATION FLIGHTS
  - HIGH OPERATIONAL RELIABILITY
  - SELF-CONTAINED FOR REMOTE OPERATIONS
- **GOALS**
  - 20 YEAR LIFETIME
  - 120 RESEARCH FLIGHTS PER YEAR WITH MAXIMUM OBSERVING TIME: 40 WEEKS/YEAR
  - 7 DAY PER WEEK OPERATIONS
  - MANAGEMENT BY CIVIL SERVICE/OPERATION BY SUPPORT SERVICE CONTRACT STAFF
  - IOC IN FY 1992 FOR SCIENCE OBSERVING OPERATIONS
  - APPROXIMATELY NINE MONTH SHAKE-DOWN PERIOD
- **SCIENCE SELECTION**
  - "DEAR COLLEAGUE" LETTER
  - LETTERS OF INTENT/PROPOSALS
  - REVIEW AND SELECTION
  - ANNOUNCEMENT OF AWARDS
  - FUNDING OF U.S. OBSERVERS BY NASA GRANT







## **SECTION II**

### **SCIENCE**

- 2.1**      **Introduction**
- 2.2**      **Perspective on Modern Astronomy**
- 2.3**      **Airborne Astronomy Background**
- 2.4**      **SOFIA Comparison with KAO**
- 2.5**      **Astronomical Promise**
- 2.6**      **A Logical Progression**
- 2.7**      **The Need for SOFIA**

## 2.1

### Introduction

In 1972 the Astronomy Survey (Greenstein) Committee Report to the National Academy of Sciences included in their "Programs of Highest Priority" a recommendation that NASA "undertake design studies for a very large stratospheric telescope." At that time, the Agency was nearing completion of the 91 cm diameter airborne telescope that was later to be christened the Gerard P. Kuiper Airborne Observatory (KAO). The unqualified success of the KAO over the past thirteen years of operation, coupled with the wealth of new infrared sources discovered by the Infrared Astronomical Satellite (IRAS), have led to the implementation of this recommendation.

This Phase A Report describes the first step of the recommended studies. This section presents the scientific background, the scientific potential, a comparison with other astronomy missions, and the overall justification for such a facility.

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TABLE 1  
INTERSTELLAR SPECTRAL FEATURES  
DETECTED FROM THE KUIPER AIRBORNE OBSERVATORY

WAVELENGTH (MICRONS)	ABSORPTION/ EMISSION	IDENTIFICATION
2.95	Abs	NH <sub>3</sub> Ice
5.0	Abs	(?) Ice Mantle
5.5	Abs	(?) Ice Mantle
5.62	Em	PAH
6.0	Abs	H <sub>2</sub> O Ice Mantles
6.2	Em	PAH
6.8	Abs	Hydrocarbon Mantles
6.95	Em	PAH
7.6	Abs	(?) PAH
7.7	Em	PAH
19.0	Abs/Em	Silicate
24-30 <sup>a</sup>	Em	MgS (?)
45	Abs	H <sub>2</sub> O Ice
1.9, 6.6, 7.5	Em	H I
4.5	Em	Mg IV, Ar VI (?)
21.8	Em	Ar III
5.6	Em	Mg V
6.6	Em	N I II
6.99	Em	Ar II
18.7, 33.4	Em	S III
24.3	Em	Ne V
25.9	Em	O IV
34.8	Em	Si II
36.0	Em	Ne II II
51.8, 88.0	Em	O III
57.3	Em	N III
63.2, 146	Em	O I
157.8	Em	C II
157.8	Em	C II (?)
370.609	Em	C I
77.84, 87.97, 100,	Em	CO
119.124, 153.163,	Em	
174.186, 650	Em	
53.4, 84.4, 84.6, 119.3,	Abs/Em	OH
119.5, 163.1, 164.4	Abs/Em	OH
120.0, 120.2	Abs/Em	<sup>18</sup> OH
149.1, 149.4	Em	CH
479	Em	HCl
124.6, 166.524	Em	NH <sub>3</sub>
790.1600	Em	H <sub>2</sub> O
805	Em	H <sub>2</sub> D <sup>+</sup>

Almost all of these features were first detected from NASA's airborne observations, and cannot be studied from ground-based sites. Whereas the dust features typically originate in regions cooler than a few hundred degrees Kelvin, the various gaseous spectral features characterize regions ranging in temperature from -10°K down to -10K.

### Perspective on Modern Astronomy

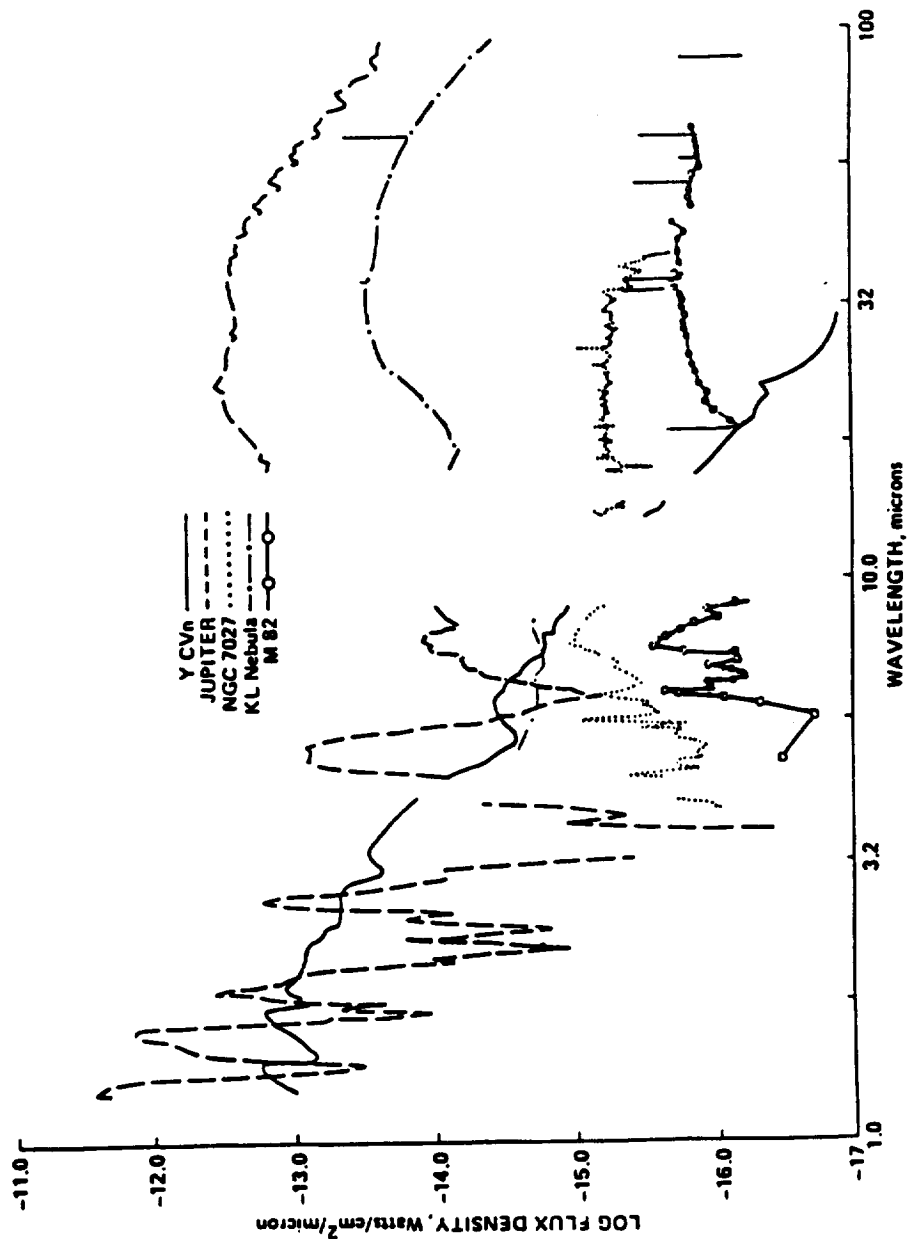
Astronomical advances of recent decades have shown that progress is based upon parallel developments along the broadest possible front and often attained with highly specialized facilities. Distant quasars, originally discovered because they appeared incredibly bright at radio wavelengths, were later shown by the Einstein Observatory to be even more powerful emitters of X-radiation, and by observations from the KAO to be powerful emitters in the infrared as well. Interstellar hydrogen molecules, first detected in the open spaces between the stars by the ultraviolet observatories Copernicus and IUE, have been traced into the dark regions of dusty molecular clouds through infrared observations conducted from the KAO.

This progress on a broad front - which is typified by the results of the Airborne Program - will clearly continue well into the 21st century, as new facilities are developed to explore the frontiers of modern astronomy. The spectacular infrared sky maps of IRAS have revealed protoplanetary material orbiting stars, diffuse "cirrus" clouds rising far above the central plane of the Milky Way, and an abundance of infrared galaxies similar to those discovered from the KAO. Most of the IRAS data remain to be exploited by further analysis and subsequent observations. NASA's Hubble Space Telescope (HST) will probe far into the universe to provide deeper cosmological insight through ultraviolet and visible observations far more sensitive than previously possible. The Gamma Ray Observatory (GRO) and the AXAF (Advanced X-Ray Astrophysics Facility) will extend our ability to observe violent relativistic processes in objects such as the nuclei of quasars, and possibly to discover new sources of high energy radiation. The European Infrared Space Observatory (ISO) will study many of the IRAS sources, and SIRTf (the Space Infrared Telescope Facility) will provide detailed studies of even the faintest IRAS sources, and will permit limited surveying to much fainter flux limits than reached by IRAS.

Early in the next century, the 8 meter diameter European Far Infrared Space Telescope (FIRST) will permit submillimeter spectroscopic studies of the interstellar medium with high angular resolution, and subsequently the roughly 20 meter diameter Large Deployable Reflector (LDR) will allow even higher spatial resolution photometric and spectroscopic observations throughout the far infrared and submillimeter domains. In the interim, a number of 10 meter class telescopes for visible, near infrared, and millimeter wavelengths will be built at ground-based sites.

However, this impressive armada of astronomical facilities is missing an important element: a major airborne observatory. To understand the value of such a facility, we consider below the potential for its capabilities compare with those of the missions cited above.

**FIGURE 1**  
**ENERGY DISTRIBUTIONS OF ASTRONOMICAL OBJECTS OBTAINED**  
**FROM THE LEARJET AND KUIPER AIRBORNE OBSERVATORIES**



### Airborne Astronomy - Background

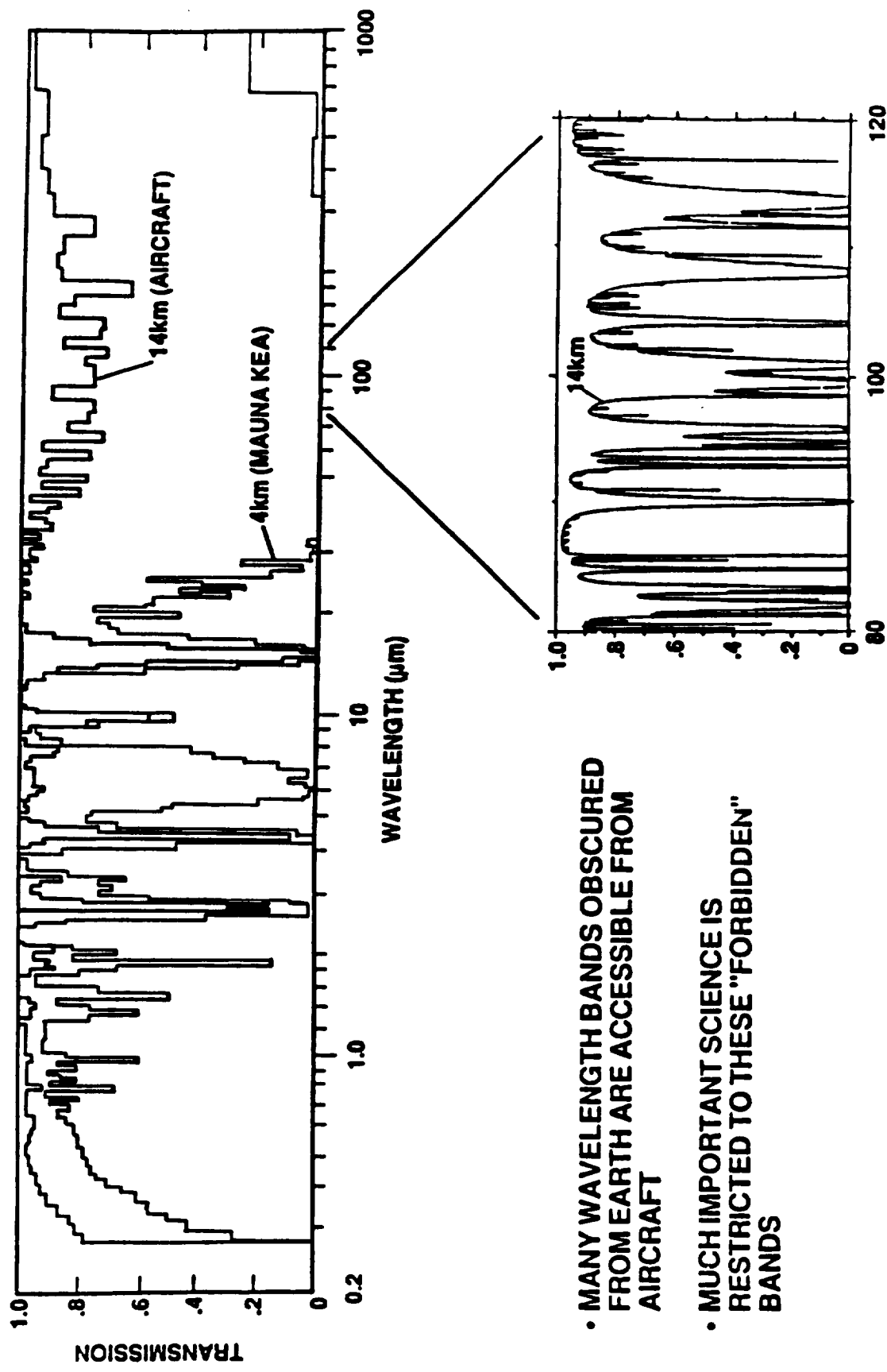
The KAO and its predecessor, the Learjet Observatory, are among the few astronomical observatories which have dominated a particular wavelength region for a significant time. Among the prominent discoveries made from the aircraft are: water in comets Halley and Wilson; rings around Uranus; intrinsic thermal emission from Jupiter, Saturn, and Neptune; infrared emission from our galactic center equivalent to the power of 10 million suns; locations, luminosities, and structures of obscured young stellar objects; some 70 spectral features of atoms, molecules, and grains which are extensively improving our understanding of the physics and chemistry of the interstellar medium (see Table 1); "infrared" galaxies which emit orders of magnitude more energy in the far-infrared than at all other wavelengths; an infrared bolometric correction of a factor of two for the luminosity of "normal" spiral galaxies; and excess infrared emission of unknown origin from quasars, the most distant astronomical objects known.

Figure 1 plots flux densities for five "classical" infrared objects in the 1-100  $\mu\text{m}$  range to indicate some of the variety of aircraft observations. (No data are shown for the band around 10  $\mu\text{m}$ , which is accessible from the ground, as is much of the 1-5  $\mu\text{m}$  range.) At the shorter wavelengths, the vibrational transitions of molecules are prominent in the gas phase, and are often manifested even when the molecules are constituents of interstellar grains. Molecular rotational transitions, which occur at the longer wavelengths, are typically frozen out when the molecule is locked in a solid. Thus Jupiter's atmosphere shows strong vibrational (1-8  $\mu\text{m}$ ) features of ammonia and methane, and rotational (40-100  $\mu\text{m}$ ) features of ammonia. In the spectrum of YCVn (a carbon star), we see molecular features due to carbon-rich molecules in a circumstellar envelope. In the Kleinman-Low object (KL, a molecular cloud with embedded invisible luminosity source) the continuum, which is due principally to re-emission of the interior luminosity by dust grains, shows some grain features in the 4-8  $\mu\text{m}$  range, but is smooth at the longer wavelengths except for a broad absorption around 45 microns probably due to water ice.

Also indicated in Figure 1 at the longer wavelengths are atomic fine structure lines in the spectra of KL NGC 7027 (a bright planetary nebula), and M82 (a star-burst galaxy). These lines provide important information on abundance, density, excitation, cooling, and dynamics of the gas. Ignored in this plot is the important spectral range 100-1000  $\mu\text{m}$ . In this range both the continuum distributions and line emissions from a variety of objects are extremely interesting. An example of particular importance to interstellar carbon chemistry are the lines of C, C<sup>+</sup>, and CO (see Table 1).

The fundamental phenomenon underlying the great success of airborne astronomy is the transmission of the earth's atmosphere at altitudes accessible to modern aircraft, which is compared to ground based transmission as a function of wavelength in Figure 2. The upper plot is at a spectral resolving power of 10%, and the lower plot shows one of the poorest transmission segments of the spectrum (80-120  $\mu\text{m}$ ) at a resolving power of 5000.

**FIGURE 2**  
**ATMOSPHERIC TRANSMISSION VERSUS WAVELENGTH**



- MANY WAVELENGTH BANDS OBSCURED FROM EARTH ARE ACCESSIBLE FROM AIRCRAFT
- MUCH IMPORTANT SCIENCE IS RESTRICTED TO THESE "FORBIDDEN" BANDS

## 2.3

### Airborne Astronomy - Background (cont'd)

The transmission from the ozone cutoff at about 0.28 microns out to about one micron is dominated by molecular and aerosol scattering. At longer wavelengths the transmission is determined largely by triatomic molecular absorptions, particularly carbon dioxide (which is uniformly mixed), water (which is stratified), and ozone (which is located high above aircraft altitudes). Water is the principle culprit in regions where the aircraft transmission greatly exceeds the mountain-top transmission. The amount of precipitable water in the figure is 10  $\mu\text{m}$  for the 14 km (aircraft) altitude and 500  $\mu\text{m}$  for the 4 km (Mauna Kea) altitude. This large difference exists because the water is located mostly below the temperature inversion in the troposphere, which may be from roughly 30,000 to 50,000 feet altitude, depending on latitude and season.

Another point is that most of the water vapor in the line of sight is relatively near the aircraft at operating altitudes. The amount of water is typically reduced by a factor of two when the altitude is increased from 41,000 to 45,000 feet. Hence some observations are only achieved by flying the observatory at the highest possible altitude.

As seen from the upper plot, practically no work can be done from the ground throughout the 30-350  $\mu\text{m}$  range. The lower plot shows that many of the absorbing water lines in this spectral range are still saturated even at aircraft altitudes. Nevertheless, a great deal of interesting science which is impossible from the ground is readily accomplished with an airborne telescope.

Some observations require the aircraft even at wavelengths where the transmission from the ground appears to be good, such as the discovery of water in comets Halley and Wilson in the 1-3  $\mu\text{m}$  range, and the study of interstellar water in Orion at 1.6 mm. Other advantages of an airborne observatory over mountain-top facilities are: (1) scintillation noise is greatly reduced at visible and ultraviolet wavelengths, (2) the reduced temperature of a telescope operating in the low stratosphere increases the background-limited sensitivity in the near infrared, (3) the observatory can readily be deployed to observe targets of opportunity, and is rarely "clouded out." For example, the discovery of rings around Uranus was made from the KAO flying off the coast of Australia by stellar photometry of an occulted star, which was the only observation of both immersion and emersion.

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TABLE 2  
ANTICIPATED SOFIA PARAMETERS (COMPARED WITH KAO)

	SOFIA		KAO	
	>6h, TBS	same	5h	7.5h
A. Flight profile:				
1 Aircraft-limited duration at >41,000 feet..				
2 Nominal flight duration (crew-limited).....				
3 Flights per year.....	120			
B. Optics				
1 Primary mirror diameter (meters).....	2.7-3	same	.3-1600um	.91
2 Wavelength range.....	same	same	Nasmyth, Cassegrain	12"
3 Telescope configurations.....	8'	same		
4 Unvignetted field of view.....	20, TBS	same	9-18	
5 Available f/ ratios.....	1.0	same	6 months	
6 Image quality of optics: circle diameter		same	Lick Observatory	
7 Enclosing 80% of optical image		same	1.5" (measured)	
8 Enclosing 80% of optical image		same	6 months	
9 Frequency.....		same	6 months	
10 Location.....		same	Lick Observatory	
C. Seeing limitations				
1 Diameter enclosing 50% of optical image.....	<3"	30um	<3" (measured)	
2 Diffraction-limited wavelength.....			<50um (measured)	
3 80% image diameter at above wavelength.....			<27" (measured)	
D. Telescope performance				
1 Pointing stability (r.m.s. error)		same	0.2" (measured)	
2 Focal plane guiding on unchopped star.....		same	5" (measured)	
3 Tracker telescope guiding.....		same, TBS	2"	
4 Faintest trackable star (tracker telescope)...		13m	11m	
5 Elevation range (degrees).....	20-60	3	35-75	
6 Maximum nodding amplitude (degrees).....		6		
7 Nodding + settling time (5' nod).....		2s		
8 Maximum slew rate (degrees/sec).....	same	0.4		
9 Gyro-stabilized range (EL & XEL, degrees).....	24, TBS		35	
E. Infrared Performance				
1 Chopping secondary:				
2 Chopping functions.....		same	chop, rotate, focus	
3 Focus modes.....		same	adjustable, dither	
4 Chopping waveforms.....		same	square, arbitrary	
5 End position stability (% of chop).....		1	3	
6 Rise time (msec) for 1 arc min chop.....		same	5	
7 Frequency range (Hz) for 1 arc min chop.....		1-35	9-13, 22-35	
8 Telescope thermal properties:				
9 emissivity (Nasmyth configuration).....		<15%	35% (measured*)	
10 nominal operating optics temperature.....		same	250K	
11 optical system thermal time constant.....		2h, TBS	8.5h	
12 mirror temperature distribution with precool.		same, TBS	15K	
13 deviation from recovery temperature.....			10K	
14 Emissivity measured with dirty mirrors.				

## 2.3

### Airborne Astronomy - Background (contd)

Perhaps the most striking aspect of Figure 2 is its broad wavelength range. Observations from the KAO have actually been made at wavelengths separated by a factor of over 5000. This means that the variety of scientific problems which can be studied from an airborne observatory is extremely diverse.

A related factor in the success of the airborne program is the extensive science community involvement in it. Over 70 principal investigators and their collaborators have written more than 500 refereed publications based on airborne observations and related studies, and more than 30 Ph.D's have been awarded for astronomical research done from the KAO and Learjet. The annual peer review of proposals typically receives requests for 3 or 4 times more flights than can be accommodated on the KAO.

TABLE 3  
FOCAL PLANE INSTRUMENTS SCHEDULED FOR USE ON THE  
KUIPER AIRBORNE OBSERVATORY IN FISCAL YEAR 1987

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PRINCIPAL INVESTIGATOR/ INSTITUTION	INSTRUMENT TYPE	WAVELENGTH RANGE	SPECTRAL RESOLUTION
E. BECKLIN/ UNIVERSITY OF HAWAII	MULTICHANNEL SOLAR PHOTO METERS	30-350 $\mu$ m	$\lambda/\Delta\lambda$ -3
A. BETZ/UNIVERSITY CALIFORNIA AT BERKELEY	HETERODYNE SPECTROMETER	150-500 $\mu$ m	$\Delta\nu$ 1 MHz
J.D. BREGMAN/ NASA AMES RESEARCH CENTER	GRATING SPECTROMETER	1-5 $\mu$ m	$\lambda/\Delta\lambda$ -100
E.F. ERICKSON/ NASA-AMES RESEARCH CENTER	ECHELLE SPECTROMETER	30-120 $\mu$ m	20,025 $\text{cm}^{-1}$
D.A. HARPER/ YERKES OBSERVATORY	PHOTOMETERS	40-400 $\mu$ m	$\lambda/\Delta\lambda$ -2-10
P.M. HARVEY/UNIVERSITY OF TEXAS AT AUSTIN	PHOTOMETERS	40-200 $\mu$ m	-20-100 $\mu$ m
T.L. HERTER/ CORNELL UNIVERSITY	GRATING SPECTROMETER	16-30 $\mu$ m	-0.03 $\mu$ m, 0.3 $\mu$ m
R.H. HILDEBRAND/ UNIVERSITY OF CHICAGO	PHOTOMETER	100-300 $\mu$ m	$\lambda/\Delta\lambda$ -2-10
H.P. LARSON/ UNIVERSITY OF ARIZONA	MICHELSON INTERFEROMETER	1-3.5 $\mu$ m	- 0.01 $\text{cm}^{-1}$
H. MOSELEY/ NASA-GODDARD	GRATING SPECTROMETERS	27-55 $\mu$ m	- 3 $\mu$ m
T.G. PHILLIPS/CALIFORNIA INSTITUTE OF TECHNOLOGY	HETERODYNE SPECTROMETER	0.4-0.85 $\mu$ m	$\lambda/\Delta\lambda$ -10 <sup>6</sup>
H.P. ROSEMAN/PLANK INSTITUT, BONN FRG	HETERODYNE SPECTROMETER	.3-1 $\mu$ m	$\lambda/\Delta\lambda$ -10 <sup>6</sup>
C.H. TOWNES/UNIVERSITY AT CALIFORNIA AT BERKELEY	FABRY-PEROT SPECTROMETER	40-200 $\mu$ m	$\lambda/\Delta\lambda$ 30,000
P.C. WANNIER/JET PROPULSION LABORATORY	TWO-BAND HETERO- DYNE SPECTROMETER	.79, 1.6 $\mu$ m	$\Delta\nu$ 100kHz
H.W. WILSON/BELL LABS	HETERODYNE SPECTROMETER	625 $\mu$ m	$\lambda/\Delta\lambda$ -10 <sup>-6</sup>
F.C. WITTEBORN/ NASA-AMES RESEARCH CENTER	GRATING SPECTROMETERS	4-14 $\mu$ m	$\lambda/\Delta\lambda$ -120, 50

## 2.4

### SOFIA Performance Comparison with KAO

Table 2 summarizes the parameters expected to be achievable for SOFIA, and compares them with the KAO. A few of these are highlighted here:

Item A.3, flights per year: It is felt by the science community that every effort should be made to permit SOFIA to be operated at the 120 flights/year level. This rate is understood to be practical based on considerations such as maintenance, instrument installation, crew training, etc.

Item B.5, available f-ratios: To simplify the design of the telescope and the installation of instruments, a single f-ratio is anticipated for SOFIA initially, with a wider range for follow-on capability (accomplished by use of different secondary mirrors).

Item B.6, image quality of optics: this is specified to be consistent with probable seeing limitations.

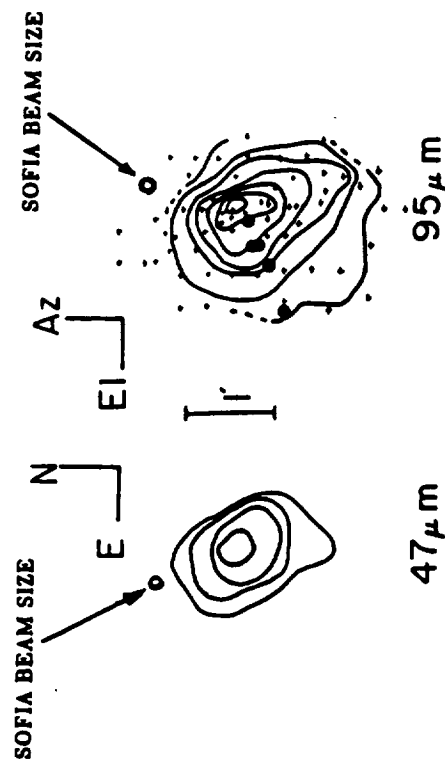
Item D.2, elevation range: The lower range for SOFIA means that sources farther south than the galactic center will be readily accessible on flights originating at NASA Ames.

Item E.1, chopping secondary: An essential feature for SOFIA, the relatively large secondary mirror (about 30 cm diameter) will require a well-designed chopper.

Item E.2, optical system thermal time constant: the large thermal time constant on the KAO is a practical impediment to rapid instrument changeovers and installation optimization. On SOFIA, the requirement of a lightweight primary should permit achieving much more rapid cooldown prior to flight.

The science program on SOFIA would be patterned after that of the KAO. This features annual peer review of both instrument proposals and guest investigator proposals. Roughly 30-40 teams might be selected in any given year, with approximately half being groups with instruments. The more sophisticated instruments may require multiple-year support during their development, but are subsequently reviewed annually. The variety of instruments is typified by the list in Table 3. Most of these instruments, which fly on the KAO, would require only minor modifications to fly on SOFIA. With its expected lifetime of 20 years, SOFIA will undoubtedly support focal plane instruments with capabilities far beyond those listed in Table 3.

**FIGURE 3**  
**CIRCUMSTELLAR DISKS AROUND LOW MASS STARS**



KAO OBSERVATIONS AT 47 AND 95  $\mu\text{m}$  OF THE SOURCE SVS 13 IN NGC 1333. THE CIRCLES REPRESENT THE DIFFRACTION LIMITED BEAM SIZE FOR A 3m APERTURE TELESCOPE.

SOFIA CAN PROVIDE SPATIAL RESOLUTION AND SENSITIVITY INCREASES OVER KAO THAT WILL ALLOW:

- DISCRIMINATION BETWEEN THIN AND THICK DISKS.
- OBSERVATION OF A STATISTICALLY SIGNIFICANT NUMBER OF SUCH DISK-LIKE SOURCES.
- DETERMINATION OF TEMPERATURE PROFILES ACROSS THE DISKS.
- DIRECT OBSERVATIONAL TESTS OF PROTOSTELLAR DISK MODELS.

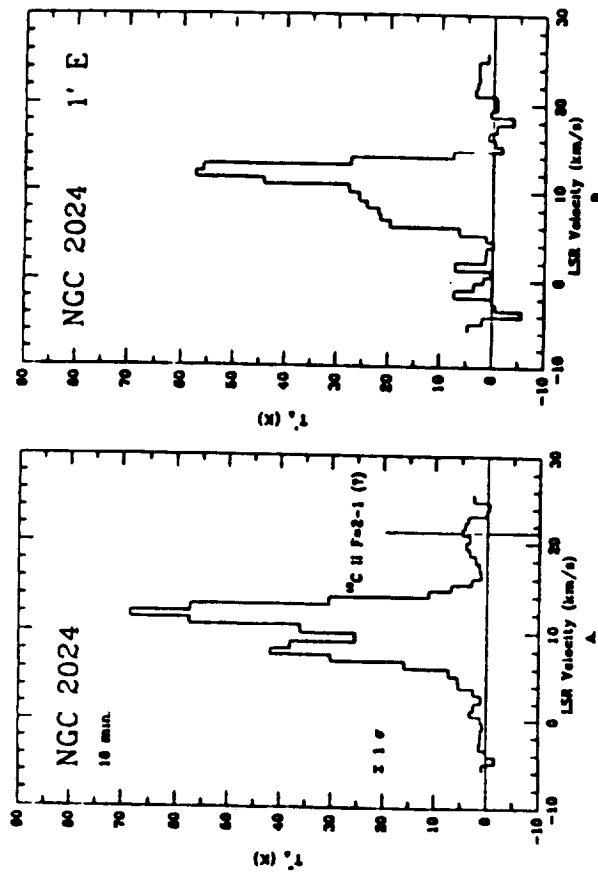
### Astronomical Promise

Suitably instrumented, SOFIA will provide images or spectra of a vast variety of fundamental phenomena. These might range from supernova outbursts in external galaxies to protostellar flows in young star-forming regions within the Milky Way. A few exciting possibilities deserve particular attention:

Star formation, as currently understood, begins with contraction of a cool, dusty, gaseous region in interstellar space. As this contraction accelerates, a compact, central condensation forms, surrounded by an orbiting disk of matter. Isolated examples of these sources have been identified from KAO observations of globules and other small clouds. More recently, the IRAS survey may have detected a cluster of such young stellar sources in the Taurus cloud. Ground-based radio and near-infrared observations generally indicate that individual protostellar objects are likely to be separated by less than 2 to 10 seconds of arc on the sky. These separations are too small for KAO or IRAS to resolve. With SOFIA, however, we could isolate and individually study such objects. We expect for the first time to detect the infall of material onto the protostellar disk surrounding the centrally condensed star. The shock produced by the gases striking the disk would heat and collisionally excite the gas atoms and molecules causing them to radiate. The shocked regions lie at such depths within the disk that only radiation at wavelengths longer than 100 microns is likely to escape unhindered. Fortunately, important diagnostic spectral features, for example from carbon monoxide, atomic oxygen, and water vapor lie at these wavelengths. A shocked protostellar accretion disk in the Taurus cloud is expected to provide a weak signal from individual emission lines, but one that could be detected with a spectrometer mounted at SOFIA's focal plane. In addition, SOFIA's good spatial resolution may allow direct photometric observation of the geometry of disks in young stellar objects. Figure 3 shows the KAO measurement of SVS 13 in NGC 1333, which has an elongated geometry suggestive of a disk. The improvement in sensitivity and spatial resolution which SOFIA could provide would permit discrimination between thin and thick disks, determination of temperature profiles across some disks, observation of a statistically significant number of disk-like sources, and direct observational tests of protostellar models.

We currently have no detailed maps of astronomical sources at wavelengths between 100 and 350 microns. While the IRAS survey does not reach beyond 100 microns, SOFIA could resolve many sources on a scale of better than 30 arc seconds at wavelengths of 200 and 350 microns. The KAO has already established the existence of a class of sources with peak emission in this wavelength range. Comparative studies made at radio wavelengths have frequently been carried out at comparable angular resolution. By combining radio data with submillimeter results obtained from SOFIA, we can gain insight into the physical conditions in extended dusty regions. From SOFIA, astronomers would map the polarized thermal emission from cool dust, and the total power radiated in atomic fine-structure and rotational molecular lines. These measurements provide estimates of density, temperature, chemical makeup, and magnetic fields in these regions. When the combined observations are

**FIGURE 4**  
**VELOCITY RESOLVED SPECTRA OF GALACTIC CLOUDS**  
**(C II) 1900.537 GHz**



KAO OBSERVATIONS OF THE 168  $\mu\text{m}$  C<sup>+</sup> LINE. THE MEASUREMENT REVEALS CLOUD COOLING RATE, GAS DYNAMICS, AND CARBON CHEMISTRY.

SOFIA WOULD

- PERMIT MAPPING TO DETECT INDIVIDUAL CLUMPS OR IONIZATION FRONTS, PROBING THE NATURE OF OBSCURED LUMINOSITY SOURCES.
- ALLOW C ABUNDANCE ESTIMATES IN OTHER OBJECTS (e.g. PLANETARY NEBULAE, LATE STELLAR ENVELOPES) TOO FAINT FOR OBSERVATIONS FROM THE KAO.

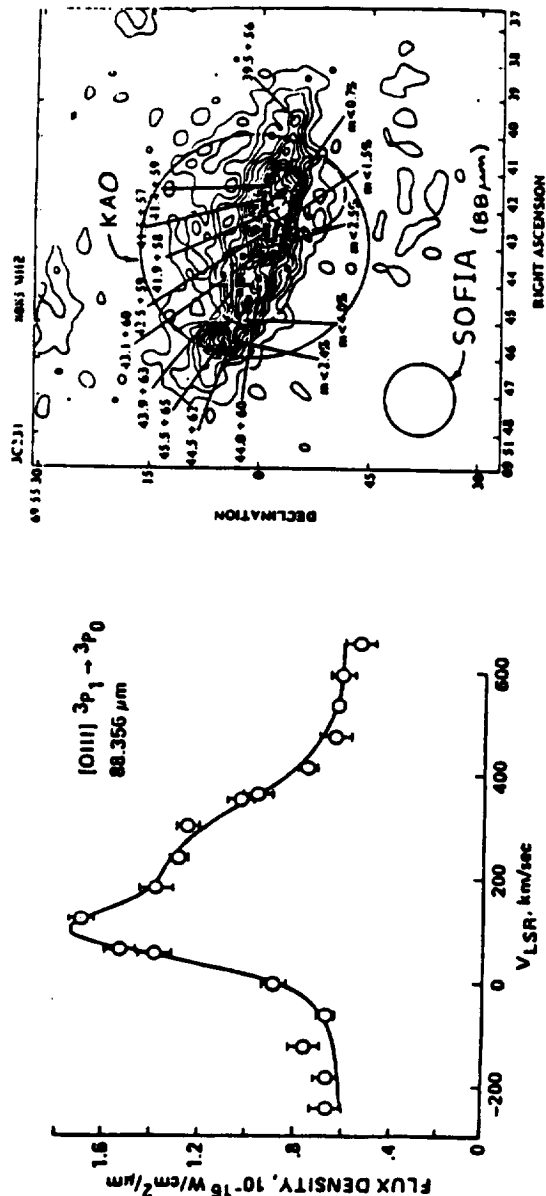
### *Astronomical Promise (contd)*

made at sufficiently high spectral resolution the lines also provide data on systematic and turbulent motions within a cloud. Velocity-resolved spectra of the 158 micron line of C+ measured from the KAO with a heterodyne receiver are shown in Figure 4. The source, a molecular-cloud/HII region complex, shows two velocity components which may arise from clumps of moving gas. SOFIA would permit mapping to detect individual clumps or ionization fronts, and would allow abundance estimates in other objects, such as planetary nebulae or late-type stellar envelopes, which are too faint for observations from the KAO.

Similarly, high spatial resolution mapping of the continuum and lines emitted by nuclei of obscured external galaxies at wavelengths from 30 to 300 microns, will provide unique evidence regarding the distribution of stellar types, the morphology of the ionized gas, and its relation to the distribution of the dust and luminous stars. Figure 5 shows a line profile of the 88 micron 0++ line from the nucleus of the starburst galaxy M2, and a radio map of the source with KAO and SOFIA beams superimposed. Velocity structure in the line suggests strong variation in the emission from different components of the source, which SOFIA could readily isolate but the KAO cannot. In fact, a whole range of Galactic astronomy problems currently being investigated from the KAO will be extended to the study of external galaxies by SOFIA. SOFIA would also permit entirely new extragalactic investigations, such as determining whether a massive burst of star formation or an obscured central object is the ultimate luminosity source in an infrared galaxy. The extensive IRAS observations of galaxies further emphasize the need for SOFIA, for example, in understanding why many interacting galaxies have high infrared luminosities.

Of course, the power of SOFIA will also be exploited on solar system objects. Observations of occultations at near-infrared, visible, and near-ultraviolet wavelengths will be made as opportunities arise, to study planetary atmospheres and ring systems. Comets, the least understood objects in the solar system, would also be prime targets for SOFIA, from which near-infrared observations should permit new insights into the properties of cometary matter and its relationship to the primitive solar nebula. Far-infrared and submillimeter images of planets will be obtained at much higher spatial and spectral resolution than that available on current spacecraft. These will provide new understanding of atmospheric phenomena of the planets and permit the study of satellites that are too close to the parent planet to be resolved by other, smaller telescopes, such as SIRTF or the KAO. Figure 6 shows the far infrared spectrum of Saturn's rings measured from the KAO. Because the rings could not be spatially resolved, the spectrum had to be obtained by subtracting spectra of the Saturnian system taken 6 years apart. SOFIA could make the same measurement on a single flight, eliminating the systematic uncertainties associated with the subtraction.

**FIGURE 5**  
**FAR INFRARED SPECTROSCOPY OF IR-BRIGHT GALAXIES**



**KAO MEASUREMENT OF O<sup>++</sup> IN  
THE STARBURST GALAXY M82.**

**RADIO MAP OF M82 NUCLEUS  
SHOWING KAO & SOFIA BEAMS.**

- IR LINES MEASURE EXCITATION, DENSITY, ABUNDANCE RATIOS THROUGHOUT  
THE VOLUME SAMPLED.

- SOFIA WOULD PERMIT:

INDEPENDENT EXAMINATION OF DISTINCT RADIO COMPONENTS.

MEASUREMENT OF A LARGE SAMPLE OF IRAS GALAXIES.

### A Logical Progression

Having established the science potential for SOFIA based on its anticipated performance, we now examine its role in NASA's cast of existing and planned astronomy programs.

Figure 7 is a plot of photometric sensitivity for point source detection versus wavelength for the KAO, IRAS, SOFIA, and the planned spaced-based facilities HST, SIRTf, and LDR. Note that increasing sensitivity is down on the ordinate. Only the values for the KAO and IRAS are empirical. However, the SOFIA curve is extrapolated for the larger aperture from the KAO curve and so should be quite reliable. The curves for HST, SIRTf, and LDR are estimated, and so can only be compared semi-quantitatively. For the KAO and SOFIA the wavelengths are dashed where observations are normally done from the ground. The LDR curve is dashed because the size and lower wavelength cutoff are not well established. A curve for ISO would lie between those for SOFIA and SIRTf.

Relative to a spaceborne observatory, an airborne telescope suffers the disadvantages of the residual atmosphere, namely reduced transmission and increased atmospheric emission. In addition, the telescope cannot be cooled much below the ambient atmospheric temperature because of condensation, so that cryogenically cooled telescopes such as ISO and SIRTf have an enormous advantage in photometric sensitivity.

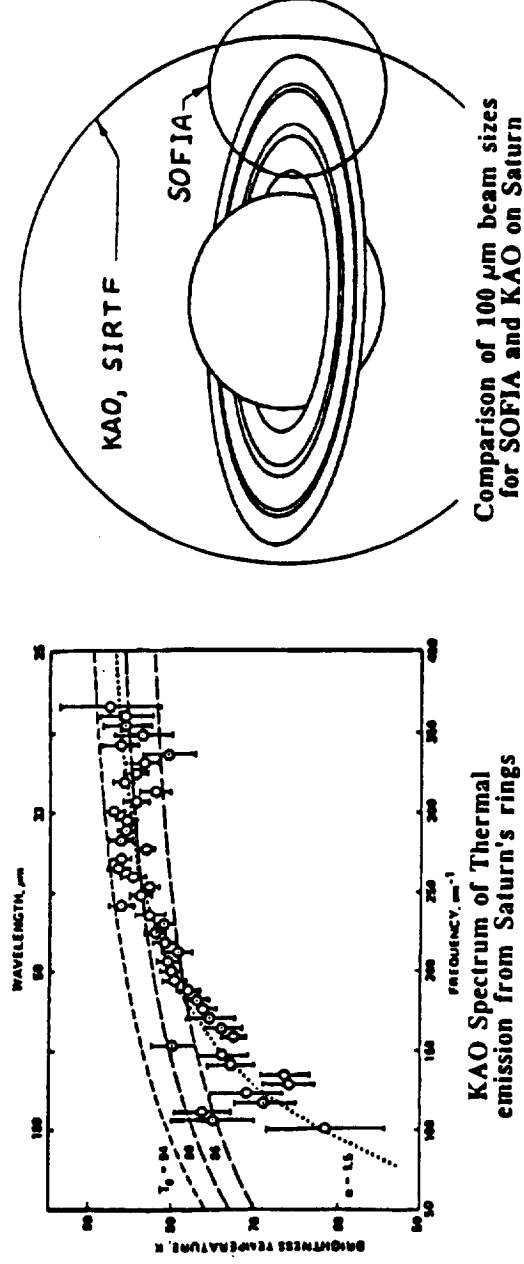
In Figure 8 angular resolution as a function of wavelength is compared for the same facilities as in Figure 7, with the addition of the IRTF on Mauna Kea. The IRTF and IRAS curves are dashed to indicate the operating wavelengths, and the LDR curve is dashed to indicate the uncertainty in the size. The curve for ISO would be similar to that for IRAS, while the FIRST curve would lie between those of SOFIA and LDR.

All the telescopes are limited by diffraction at their longer operating wavelengths. At the shorter wavelengths, HST and SIRTf are limited by the telescope optics, whereas the IRTF, KAO, and SOFIA are limited by seeing. Although the best optical images obtained on the KAO to date are about 3", it is believed that the shear layer over the open port - which is the ultimate limitation - would degrade stellar images only by about 1". Hence it is thought that the 3" limit shown for SOFIA is conservative, assuming a careful design of the facility.

Clearly SOFIA will complement ISO and SIRTf by providing higher spatial resolution, whereas these cryogenic telescopes will permit higher photometric sensitivity.

Anticipated spectroscopic resolving power is shown as a function of wavelength in Figure 9 for the same facilities as in Figure 7. For the ambient temperature telescopes, higher spectral resolution reduces the background and so leads to higher sensitivity. Lower resolution instruments take better

**FIGURE 6**  
**COMPOSITION AND STRUCTURE OF PLANETARY RING SYSTEMS**



- Far infrared KAO spectrum suggests small particle constituent
- SOFIA would permit:
- Spectroscopy of the rings on a routine basis to study composition
  - Observation of stellar occultations to determine the structure with ~1km resolution

ALogical Progression (contd)

advantage of the reduced backgrounds provided by cryogenically cooled telescopes, so for example the SIRTf instrument complement does not include a high resolution spectrometer.

For SOFIA it is expected that new technology will permit extension of heterodyne techniques from 100+  $\mu\text{m}$  range recently achieved into the 10+  $\mu\text{m}$  range, and improve the sensitivity of these receivers by large factors. Naturally this and other focal plane technology - such as integrated far infrared arrays - used on SOFIA will be transferred to FIRST and LDR, so that SOFIA will serve as the major precursor to these facilities.

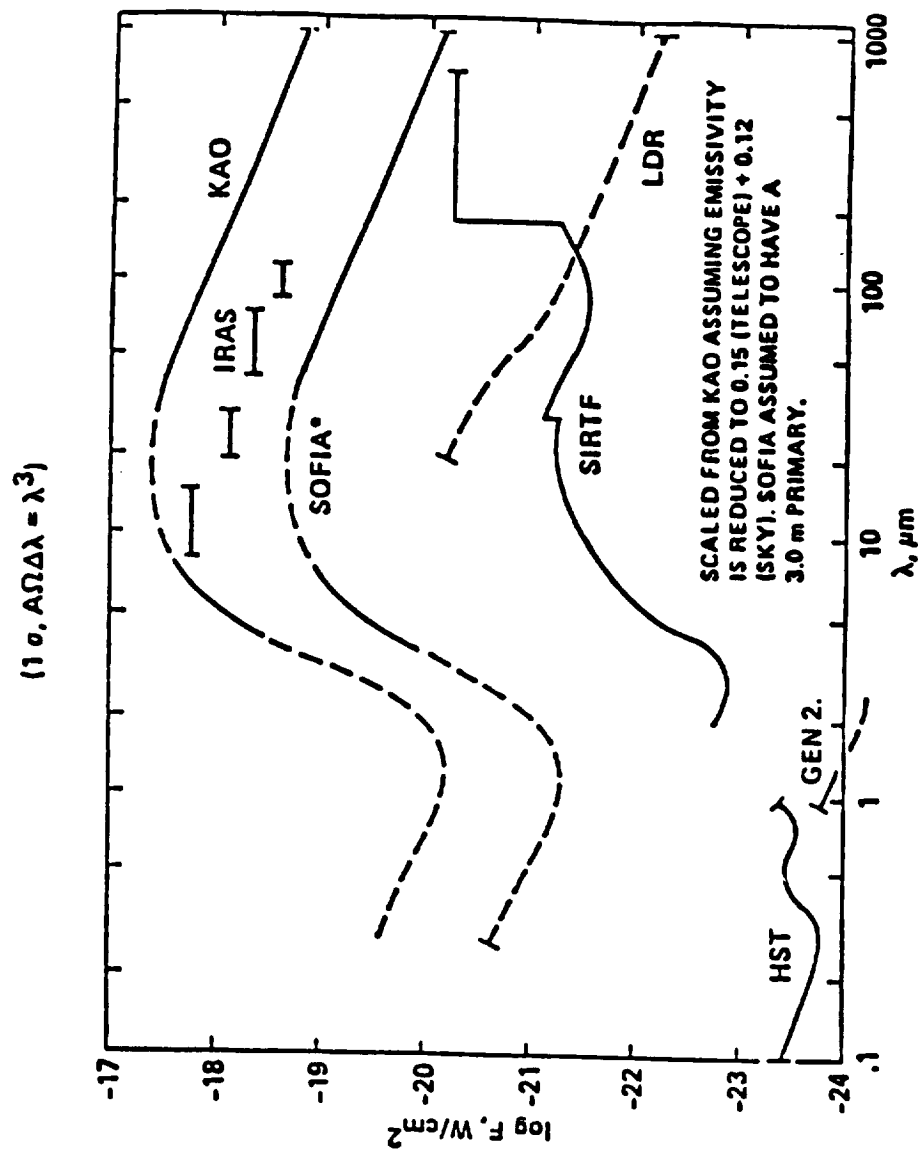
The operating intervals for realized and planned non ground-based telescopes is put in perspective on Figure 10. The long lifetimes of the airborne facilities relative to space-based programs is striking. Of course the space missions in fact have more observing hours. However, the aircraft observatories provide a continuity in terms of personnel training and technology development opportunities, which transcend the space astronomy operations.

From the foregoing technical considerations, it is clear that SOFIA would be a major advance over the KAO and would be invaluable for investigating IRAS sources. Assuming a 3 meter aperture, for compact sources it would be 10 times more sensitive, take data 100 times faster, have greater than 3 times better angular resolution, and be able to carry out observations in a volume of space nearly 40 times that of the KAO. Whereas the KAO can detect only about 15 percent of the far infrared IRAS survey point-sources, SOFIA could detect all of them!

The character of SOFIA will make it a valuable complement to ISO and SIRTf. If development is started promptly, SOFIA could be flying during the ISO mission, and five or more years before SIRTf is launched. It would thereby be able to elucidate the character of many ISO sources and provide invaluable observations of IRAS sources to help plan the SIRTf observing program. After SIRTf is launched, SOFIA could study the brighter SIRTf sources at higher spatial and spectral resolution than obtainable from SIRTf. Of course, ISO and SIRTf will have higher sensitivity for broad band and low-to-moderate spectral resolution observations, so that duplication of the observations from the cryogenic telescopes would not be attempted from SOFIA.

SOFIA's role as the stepping stone to FIRST and LDR was mentioned above. As a facility which is readily reconfigured for particular observations, SOFIA would allow detailed infrared studies to promptly investigate the discoveries obtained with other major facilities such as HST, AXAF, and GRO. Simultaneous observations could even be scheduled with a minimum of advance notice. Thus it is clear that SOFIA is a natural and important element in the overall progression of NASA's

FIGURE 7  
PHOTOMETRIC SENSITIVITY

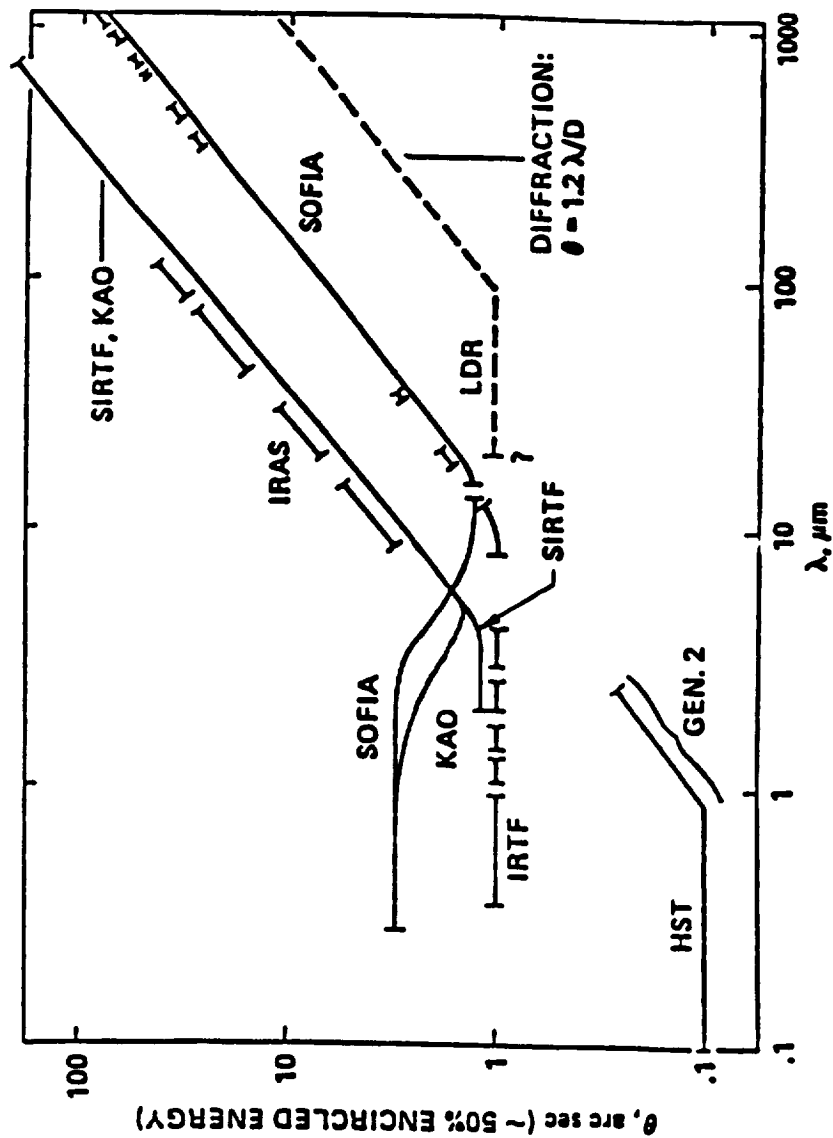


## 2.6

### A Logical Progression (contd)

In space parlance SOFIA is an observatory class facility, readily accessible to the science community with a short turn-around time, flown on a reliable, reusable "launch" vehicle. Annual peer review assures broad community involvement, rapid implementation of new focal plane technology, and prompt response to ephemeral scientific opportunities. Truly, SOFIA would be a facility with tremendous potential for science which cannot be done from earth, while remaining unencumbered by many of the difficulties associated with space missions.

FIGURE 8  
ANGULAR RESOLUTION



### The Need for SOFIA

The above discussion confirms that SOFIA will satisfy the following critical needs in astronomy which will not be met by any other observatory foreseen in this century:

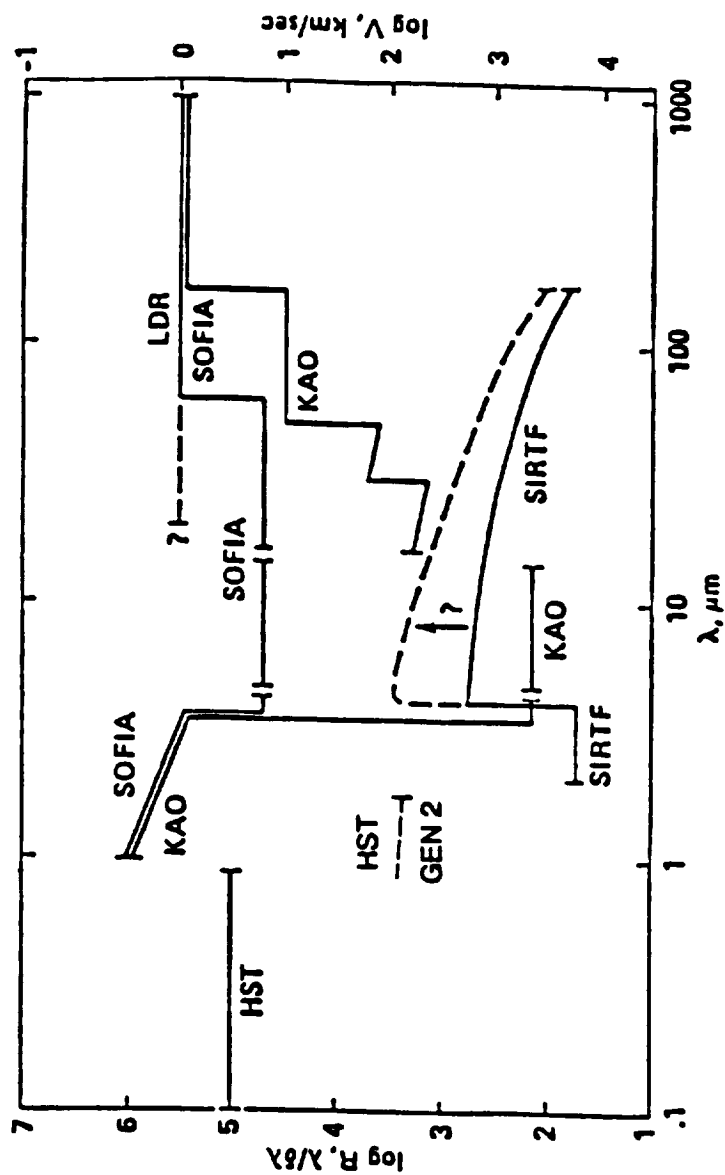
- (a) The need for higher angular resolution at infrared wavelengths which are inaccessible from the ground
- (b) The need for increased sensitivity at high spectral resolution, and
- (c) The need for an interim facility leading to the spaceborne 8 meter FIRST and 20 meter class LDR anticipated in the first decade of the 21st century

The first need - for higher angular resolution - is demonstrated by the complex structure of star-forming regions in our Galaxy, and of nuclear regions in our galaxy and in external galaxies. This structure is seen at those wavelengths observable from the ground, where the resolution is typically about an arcsecond at 10 microns and 30 arcseconds at 350 microns. These objects usually emit most of their energy at wavelengths between 30 and 300 microns, a range completely inaccessible from the ground. The KAO is the only observatory now available for routine study of these important sources at the peak wavelengths, but diffraction in its relatively small aperture causes its angular resolution to be 10 to 30 times worse than that attainable in optical or radio regions of the spectrum. The crucial infrared imaging provided by SOFIA would permit far more detailed comparison of the structures and luminosities of these objects at all wavelengths.

The second need - for increased sensitivity at high spectral resolution - is motivated by important but faint atomic and molecular features arising in the interstellar medium. The photon fluctuation noise produced by an ambient temperature telescope is much reduced by the narrow bandwidths associated with high resolution spectroscopy. In this regime the advantage of a refrigerated telescope is minimized, which is a major reason why no high resolution (~ 1 km/s) spectrometers are foreseen on ISO and SIRTf. However, the sensitivity increases as the square of the telescope diameter for compact sources. Thus for example SOFIA will allow us to study molecular gas motions deep in the interiors of dust-shrouded globules and massive molecular clouds, to search for rare constituents that are interim products of chemical reactions in such clouds, to detect light hydrides (such as HCl) and carbon ring molecules, and to study gas dynamics and physical processes in galactic nuclei.

The third need - a logical transition from the KAO to FIRST and LDR - is perceived in the context of the Hubble Space Telescope development. Whereas for HST there is an extensive tradition, a large community of qualified astronomers, and a long history of instrumentation for observations at ultraviolet and visible wavelengths, the contrary is true for the far-infrared. Indeed, the airborne

FIGURE 9  
SPECTRAL RESOLVING POWER



## 2.7

### The Need for SOFIA (cont'd)

astronomy program has been a major factor in the development of:

- (a) Scientific background
- (b) Observing techniques
- (c) Instrumentation
- (d) Personnel in the discipline of infrared astronomy

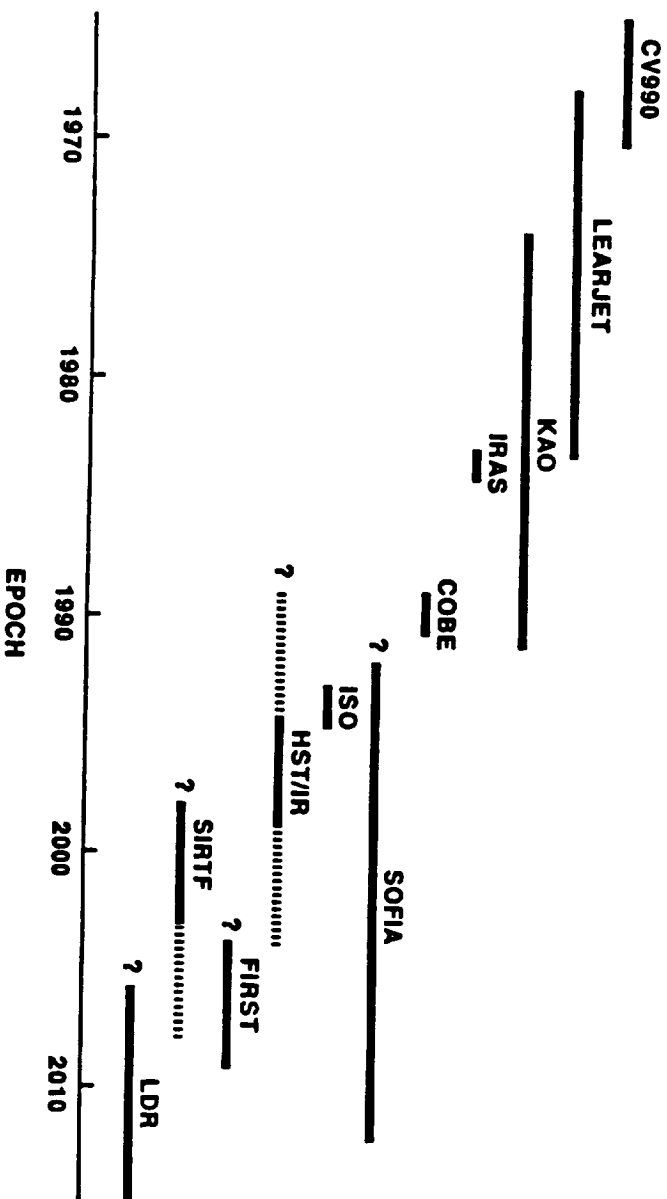
However, the discipline needs to be further strengthened to undertake a project the size of LDR. SOFIA would effectively bridge the gap between KAO and LDR in all four of the vital areas cited above. Its improved sensitivity and angular resolution, the "hands on" working environment, and the annual opportunities for proposing new science and instrumentation, assure a lively and productive program well into the 21st century.

In addition to fulfilling these needs, SOFIA would retain the unique features of its predecessors: wavelength coverage from the near ultraviolet to millimeter wavelengths, and deployability for observations of ephemeral events such as comets, eclipses, occultations, and novae.

To put the project in perspective, one has only to remember that the 0.9 meter KAO telescope is the sole observatory-class facility routinely available for most of the infrared spectral range. Imagine what the demand for a larger ground-based telescope would be if the only one in existence had a 0.9 meter aperture!

Thus, it is clear that SOFIA will provide a rich harvest of astronomical results, and concurrently support preparations for planned far-infrared and submillimeter space astronomy missions. SOFIA is needed to take its place among the world's unique astronomical facilities.

**FIGURE 10**  
**AIRBORNE AND SPACE IR ASTRONOMY OPERATIONS SYNOPSIS**









## **SECTION 3**

### **TELESCOPE SYSTEM DESCRIPTION**

- 3.1**      **Scope**
- 3.2**      **Configuration Summary**
- 3.3**      **System Budgets and Constraints**
- 3.4**      **Top-Level Interfaces**
- 3.5**      **Summary and Conclusions**

### 3.0

## TELESCOPE SYSTEM DESCRIPTION

### 3.1

#### Scope

This section contains information on the SOFIA Telescope System from a System Engineering perspective; specific subsystems' analyses and concepts are addressed in Section 4, and the Aircraft System, Ground Support System, and Operations are described in other sections. First, a brief configuration summary of the Phase A Telescope System concept is presented, including a physical description of the telescope structure/optical assembly with major trades/alternatives, the control/communications system, and miscellaneous supporting components. Next, the top-level Telescope System budgets and constraints are presented, consisting of a requirements "flowdown," optics and pointing budgets, and volume/mass constraints and budgets, including mass "status." The summary continues with an overview of system interfaces, including a communications block diagram and subsystem interface requirements. The final subsection summarizes the concept and assesses feasibility; and presents major system issues and technology drivers requiring near-term analysis, reassessment, or optimization to establish detailed feasibility against current system requirements.

## **TELESCOPE SYSTEM SUMMARY - SCOPE**

- CONFIGURATION SUMMARY
  - TELESCOPE "SUBSYSTEM" (OPTICAL ASSEMBLY/STRUCTURE); MAJOR TRADES
  - CONTROL/COMMUNICATIONS SYSTEM
  - MISCELLANEOUS COMPONENTS
- BUDGETS AND CONSTRAINTS
  - REQUIREMENTS FLOWDOWN
  - TOP-LEVEL OPTICS/POINTING BUDGETS
  - VOLUME AND MASS CONSTRAINTS/BUDGETS; STATUS
- INTERFACES
  - BLOCK DIAGRAM (TOP-LEVEL)
  - COMPONENT INTERFACES
- CONCLUSIONS
  - KEY FINDINGS/FEASIBILITY
  - MAJOR SYSTEM ISSUES

### 3.2

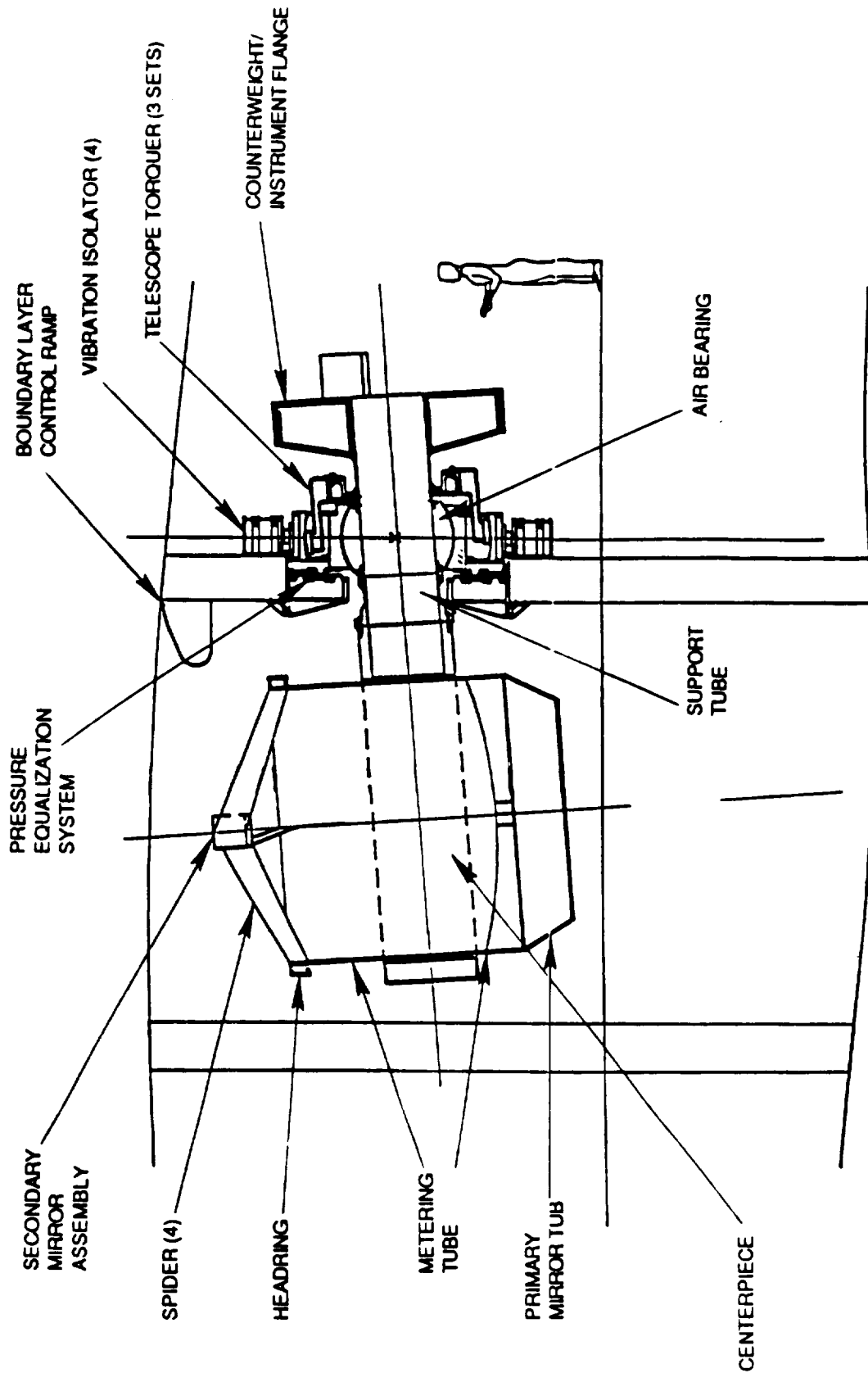
#### Configuration Summary

The chart illustrates the physical layout of the Telescope "subsystem" concept (optics, counterweight and structure), as mounted on the aft cavity bulkhead in a modified Boeing 747-SP. The optical assembly consists of a generic Cassegrain configuration, with  $\sim f/1$  primary mirror supported in a removable "tub," a removable heading/spider assembly supporting interchangeable chopping secondary mirrors (system  $f/11$  (Cassegrain) and  $f/13.5-17$  (Nasmyth)), and a flat reflecting tertiary mirror (not shown) to direct the beam  $90^\circ$  aft to a Nasmyth instrument. A Cassegrain instrument would mount below the primary mirror tub.

The optical train is supported by the Telescope structural elements, consisting of the two-section metering tube of graphite-epoxy/aluminum sandwich construction, an aluminum centerpiece ring, and Invar tubes attached to either side of a spherical air bearing, also of Invar. The counterweight/instrument flange (cabin side) balances the moments at the air bearing center and supports the Nasmyth instrument; the configuration for this element is very preliminary. The hollow air bearing, which has a  $\sim 31$  inch diameter inner "hole" and 48-inch outer diameter, allows unlimited Telescope elevation range and  $\pm 5^\circ$  cross-elevation/LOS motion.

Shown also is a set of electromagnetic torquers, just outside of the air bearing stator, for Telescope pointing control. On the cavity side of these torquers is a pressure-equalization device to eliminate cavity-cabin pressure differential across the air bearing. Finally, external to the torquers, are the vertical actuators for the pneumatic vibration isolation system; the horizontal actuators are not shown. This system isolates aircraft structure-borne vibrations from the Telescope structure.

## TELESCOPE SUBSYSTEM - PHYSICAL LAYOUT



## Design Summary

Pertinent details of the Telescope System concept are summarized. An aggressive weight goal for the system (including air bearing and counterweight) is 30,000 lbs;  $sgc$  weight breakdown/status in Section 3.3. This goal is highly dependent on achieving the  $110 \text{ kg/m}^2$  "areal density" goal for the 3-meter primary mirror facesheet; the mirror core/backface is expected to have about the same mass. A 48-point axial, 12-point lateral self-adjusting pneumatic primary support system of Graphite-Epoxy (G/E) is envisioned, based on an existing ground-based 3.5 m Telescope design. A glass secondary mirror with a 2-axis chopper requires 50-Newton actuators, and a ~225 Hz bandwidth controller to meet the chopping requirements.

The Telescope Pointing and Control System torquers are similar in design to the KAO system, using electromagnetic actuator segments attached to the Telescope for 3-axis pointing. The inertial reference units (gyros) are the rate-integrating type, using "medium technology" gas bearings, which should be adequate for the SOFIA application. The acquisition and tracker cameras are envisioned as ISIT and CCD types.

The current bearing concept is a spherical air bearing (scaled up KAO type), requiring ~40 standard cubic feet/minute of air at 265 psi, with a rotor outer diameter of 48 inches and a very stringent air gap of less than 1/1000 inch. The four-point vibration isolation system utilizes active pneumatic "air spring" actuators during normal tracking operation, internal snubbers to restrict deflections during gust loads, and external snubbers to preclude "bottoming" during hard (or crash) landings.

### TELESCOPE DESIGN SUMMARY

MASS GOAL	30,000 LBS
OPTICS	CASSEGRAIN, f/11-f/18 SYSTEM
PRIMARY	3.0 M DIA...f/1...ULE...110 Kg/SQ. M. (FACESHEET)
PRIMARY SUPPORT	G/E...ACTIVE PNEUMATIC 48 PT AXIAL AND 12 LATERAL SUPPORTS
SECONDARY	GLASS
CHOPPER	FULL 2 AXIS ELECTROMAGNETIC...50 N ACTUATOR 225 Hz BW
STRUCTURE	ALUMINUM/G/E HYBRID METERING TUBE
TORQUERS	SEGMENTED SPHERICAL MAGNETIC
GYROS	GAS BEARING RATE INTEGRATING
CAMERAS	ISIT AND CCD
AIRBEARING	SPHERE, 5 DEG ROTATION AZIM/LOS 40 SCFM/265 PSIA...DIA = 48" AIR GAP = .00096"
VIB ISOLATION	AIR SPRINGS...INTERNAL SNUBBERS

### Major Telescope System Trade-offs

Many alternative concepts were analyzed for the various elements of the Telescope System. Some of the major trades are shown on the chart, with the concepts selected written in italics; more details are provided in Section 4.

A component of overriding importance and technological complexity for SOFIA is the ~3.0 meter, *f/1* primary mirror, which must have very low mass and yet provide optical quality imaging. The ARC concept for this mirror, based on inputs from major U.S. optics manufacturers, is an "ultra-low expansion" (ULE) silica material in a structured (web-backed) configuration; this represents an extension of the technology used on the Hubble Space Telescope 2.4 m mirror. The multi-point mirror mounting subsystem, which must control mirror position and surface deflections over changing load conditions (e.g., elevation angle), is envisioned as an "active" subsystem employing pneumatically driven pistons; piston forces will be controlled by a preprogrammed routine, i.e., no feedback control loop is envisioned.

The Telescope metering structure material was iterated several times, with graphite-epoxy/aluminum sandwich chosen for weight and thermal advantages; the centerpiece material selected is aluminum and the airbearing/support tubes are of Invar. A metering "tube" was selected over truss designs for modeling simplicity, although further analysis of several factors may change this.

The secondary mirror chopper was found not to require a "reactionless" design from a dynamics perspective, and thus power dissipation can be minimized. A two-axis mechanism using existing technology (as opposed to single-axis with rotation) was selected for operational flexibility. The primary mirror temperature control will require forced gas "blowing" to minimize its time constant. Gyros will likely use gas as opposed to ball bearings or dry rotors, and appear to be more effective when attached to the instrument flange, vs the Telescope. A major trade was the support system: after reviewing many concepts it still appears that a KAO-type air bearing is most promising, but it should be demonstrated.

## MAJOR TRADES

MIRROR MATERIAL	BORO. SIL. vs. ULE STRUCTURED VS MEMBRANE ACTIVE vs PASSIVE INVAR-G/E-AL-/HYBRID TUBE VS TRUSS
MIRROR MOUNT	
TELESCOPE STRUCTURE	REACTIONLESS vs UNBALANCED SINGLE vs TWO AXIS PASSIVE-vs FORCED GAS BLOWING TYPE
CHOPPER	
THERMAL CONTROL	
GYROS	LOCATION:ON TELESCOPE vs INST. SPHERICAL vs MULTIPOINT
AIRBEARING	

#### Data Management, Acquisition and Communications System Concept

A distinct element of the SOFIA Telescope System is that portion required to provide Telescope, science and mission command, control, and communications. Since this system is not subject to questions of feasibility, a detailed engineering assessment has not been warranted; however, a top-level conceptualization of architecture and implementation was performed to assess system requirements and provide a basis for cost estimating. It was noted that simple transfer of the existing KAO system to SOFIA was not desirable, due to its limited capabilities, reliability/maintainability issues, and difficulty of upgrading; however, a system modeled after the KAO configuration (with upgrades) is warranted. Additional requirements for the SOFIA system include: reliability considerations, with high mean time between failures and noise immunity, and redundant elements (e.g., Central Processing Unit) available for immediate switchover; modifiability, by using standardized hardware and communication protocols to allow simplified change and expansion; a network concept allowing direct subsystem-to subsystem communications and ease of system build-up; a ground station (hardwire) link to enhance experiment integration and increase user efficiency; and addition of Network Manager and Test Work Stations to provide network configuring and system maintenance. Further details of the planned configuration are provided in Section 4.5.

### **DATA MANAGEMENT, ACQUISITION AND COMMUNICATIONS SYSTEM CONCEPT**

- REQUIREMENTS
  - HIGH RELIABILITY
  - REDUNDANCY
  - MODIFIABILITY/EXPANDABILITY
  - NETWORK-INDUSTRY STANDARD
  - COMMERCIAL/OFF-THE-SHELF COMPONENTS
- DESIGN GUIDELINES
  - USE KAO AS SYSTEM MODEL
  - INCORPORATE PLANNED KAO UPGRADES AND ADDITIONAL ENHANCEMENTS
  - UTILIZE NETWORK CONCEPT FOR DIRECT DATA COMMUNICATIONS
  - ADD BACKUP DATA CPU
  - STANDARDIZED HARDWARE AND COMMUNICATIONS PROTOCOL
  - ADD GROUND STATION LINK TO ENHANCE USER INTEGRATION
  - ADD NETWORK MANAGER FOR NETWORK CONFIGURING
  - ADD TEST WORK STATION FOR ENHANCED MAINTENANCE

### Major System Elements

The chart lists major elements to be included in the SOFIA Data Management, Acquisition and Communications System. Numerous sensors and actuators are distributed throughout the Telescope and cavity requiring data acquisition, display and logging, and command generation to operate mission equipment. For example, temperature sensors will be installed at several locations in the cavity and on the Telescope, and their outputs must be monitored/logged to ensure that a proper environment is maintained and to assist investigators' data interpretation. Another example is the tracker camera or chopping secondary mirror, where position sensor outputs (e.g., zoom, focus, filter, chop waveform, etc.) are provided to system operators who monitor and control (through commands to actuators) the functions of these components. The various major elements all interact through a broadband LAN and/or video distribution network, with a central processor unit (CPU) providing the central communications and processing node. The elements all utilize certain functional units or services provided by the system (as needed), including: the Local Area Network, the Central Processing Unit, a control panel/workstation, a control interface, sensors/transducers/actuators, firmware/software, and mass storage. A more detailed description of the system elements and services used is provided in Section 4.5. A system block diagram and interface summary is provided in Section 3.4, "Interfaces."

### **DATA MANAGEMENT, ACQUISITION AND COMMUNICATIONS SYSTEM MAJOR ELEMENTS**

HOUSEKEEPING AND DATA ACQUISITION SUBSYSTEM	MISC. PERIPHERAL EQUIP. (E.G., SENSORS/ACTUATORS)
DATA CPU SUBSYSTEM AND BACKUP	CAVITY ENVIRONMENTAL CONTROL SUBSYSTEM INTERFACE
TELESCOPE SYSTEM SUPPORT SUBSYSTEM	VIDEO SIGNAL PROCESSOR SUBSYSTEM INTERFACE
PRINCIPAL INVESTIGATOR SUBSYSTEM	VIBRATION ISOLATION SUBSYSTEM INTERFACE
MISSION MANAGER WORK STATION	TELESCOPE INERTIAL POINTING SUBSYSTEM INTERFACE
TELESCOPE OPERATOR WORK STATION	ACQUISITION/STAR TRACKER SUBSYSTEM INTERFACE
TRACKER SYSTEM OPERATOR WORK STATION	OFFSET GUIDER SUBSYSTEM INTERFACE
NETWORK MANAGER AND TEST WORK STATION	OSCILLATING SECONDARY MIRROR SUBSYSTEM INTERFACE
REMOTE P.I. WORK STATION	VIDEO DISTRIBUTION SUBSYSTEM INTERFACE
BROADBAND LOCAL AREA NETWORK	GROUND BASE SYSTEM AND SYSTEM LINK

## Control and Monitoring Systems

The chart lists the SOFIA Telescope and Mission System functions which require control and/or monitoring by mission operations or experimenter personnel. For each functional element, identification of the type of control/control system is given and the need for "front panel" (console/workstation) display or indication is shown; all functions require front panel controls for actuation. The functions are controlled/displayed at either the Telescope Operator Workstation, the Mission Manager Workstation, the Tracker Operator Workstation, or the Investigator Workstation(s). Some displays/indicators are shared by two or more workstations, or may be manually or automatically controlled. For example: the tracker (video) field is controlled by the Tracker Operator, but may also be displayed at the Experimenter Workstation; the secondary mirror chopper and focus can be controlled by either the Telescope Operator or the Experimenter; Telescope caging may be activated automatically (for loads or torquer capability exceedance) or manually by the Telescope Operator; target acquisition and tracking can be performed manually by the tracker operator or automatically (in the current SOFIA concept) by an automatic video tracking system. Functions such as Telescope stabilization, vibration isolation, and fine balancing are performed automatically with feedback (FB) control loops, but are also displayed for monitoring purposes.

## CONTROL AND MONITORING SYSTEMS

	CONTROL SYSTEM TYPE	FRONT PANEL CONTROLS	FRONT PANEL DISP/INDIC
BOUNDARY LAYER FENCE CONTROL	DISP CNTL W/BRAKE	X	X
COARSE TELESCOPE ELEV CONTROL	DISP CNTL W/BRAKE	X	X
APERTURE DOOR	DISP CNTL W/BRAKE	X	X
APERTURE SHIELD	OPEN-CLOSE W/BRAKE	X	X
PRESSURE WINDOW WHEEL	DISP CNTL W/BRAKE	X	X
TELESCOPE AUTO BALANCE	DISP CONTROL	X	X
TELESCOPE SYSTEM ACTIV/SHUTDN	DISCRETE LOGIC	X	X
TELESCOPE STABILIZATION	CMPLX FB CNTL	X	X
TARGET ACQ & TRACKING	CMPLX FB CNTL	X	X
CHOPPER DRIVE	CMPLX ANLG/DIG FB	X	X
SECONDARY MIRROR FOCUS	DISP CONTROL	X	X
MECH OFFSET POINTING	DISP CONTROL	X	X
TELESCOPE AUTO CENTERING	ACTIVATION LOGIC	X	X
TELESCOPE CAGING	ACTIVATION LOGIC	X	X
AIR BEARING	ACTIVATION LOGIC	X	X
TELESCOPE ATTITUDE READOUT	ACTIV LGC/ANLG/DIG	X	X
TELESCOPE SYSTEM FAULT ANNUNC	DISCRETE LOGIC	X	X
SYSTEM INTERCOM	AUDIO	X	
VIDEO DISTRIBUTION	VIDEO SWTCHG	X	
EXPERIMENTER POWER DIST	DISTRIBUTION LOGIC	X	
VACUUM SYSTEM	ACTIVATION LOGIC	X	X
VIBRATION ISOL SYSTEM	COMPLEX FB CNTL	X	X

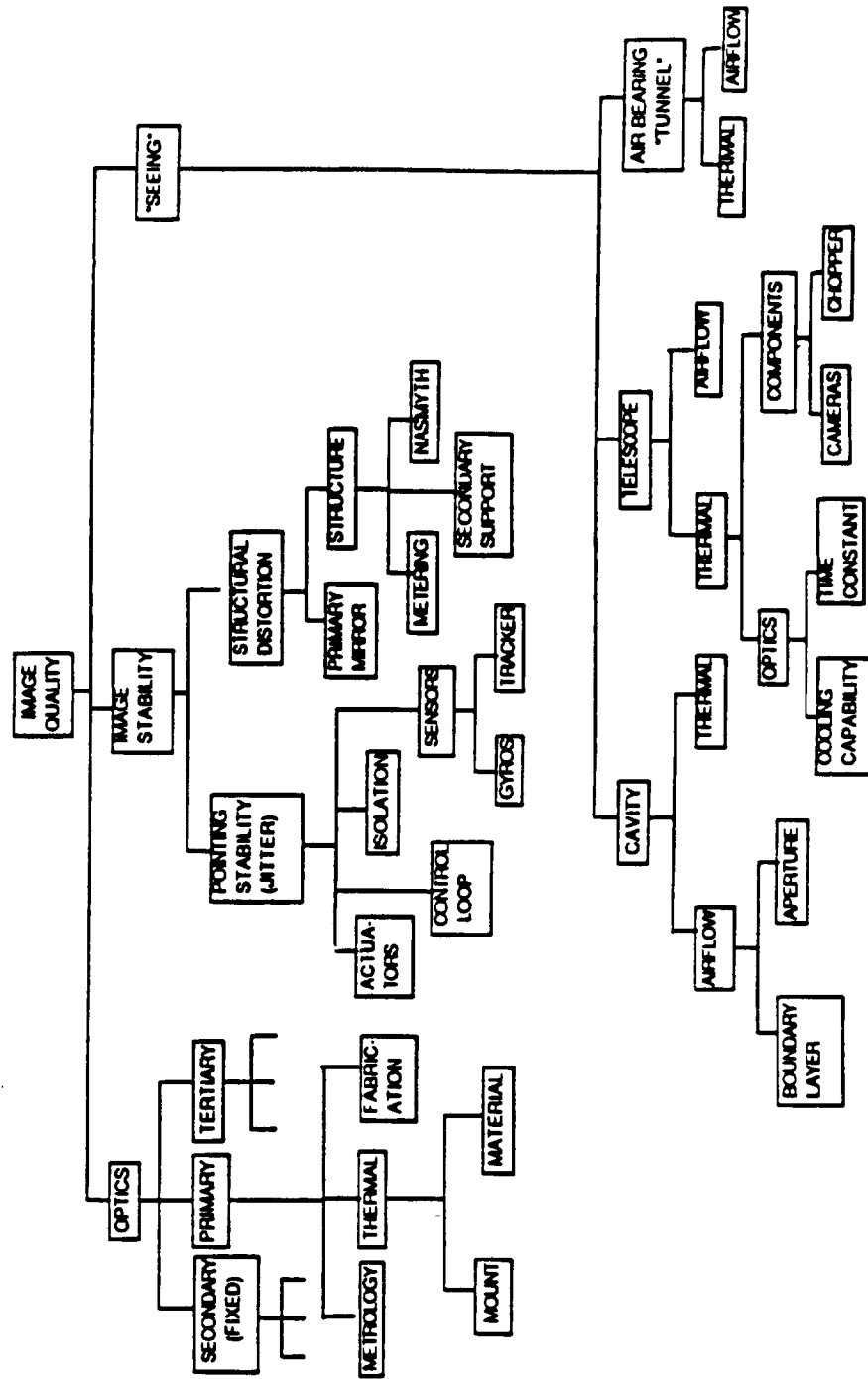
### 3.3

#### System Budgets and Constraints

##### Requirements Flowdown

To initiate the process of developing system "error budgets" a hierarchical itemization of error contributors is developed; the chart illustrates an example of this process for the critical area of image quality. Others were developed for sensitivity, functional capability, and observational and operational efficiency. As can be seen, contributors to image quality degradation are numerous for an airborne astronomical Telescope, with the major categories including the optics (mirrors), image stability (pointing and control, and structural stability), and "seeing." Within the optics category are the three mirrors, under each of which is considered contributions from mirror metrology, thermal distortions, and fabrication errors. (An additional budget is developed for cases where the secondary mirror is scanned or chopped.) Under image stability, two major categories are: the Telescope pointing stability, considering loads and structural dynamics, and performance of sensors, control system and actuators; and structural distortion due to variable loads and thermal environments. The "seeing" contribution is divided into effects from: cavity/boundary layer/airflow density fluctuation and structure; Telescope-generated or contained density variations; and effects within the air bearing tunnel (expected to be insignificant). The following pages contain top-level optics and tracking system error budgets, a Telescope volume/geometry constraint "budget," and system and Telescope mass budgets. Other lower-level budgets and constraints (e.g., structural rigidity and distortion) are contained in the subsystem descriptions in Section 4.

## REQUIREMENTS FLOWDOWN - EXAMPLE



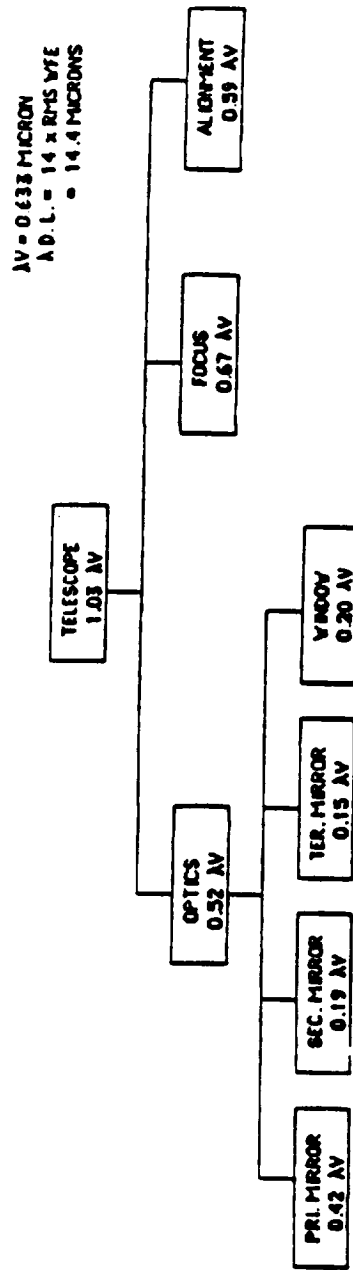
### Top-Level Error Budgets

The chart shows the first tier of error budgets developed for the Telescope optical assembly ("Wavefront Error") and the SOFIA Pointing and Control System ("Tracking Error"). Both budgets are felt to be extremely stringent, and, if achievable, would give the Telescope diffraction-limited performance in the range of 7 microns (ignoring the effects of seeing). The wavefront error budget for the 3-meter aperture spot size requirement includes contributions from the optics (mirrors/window), focus errors, and alignment errors. Another more stringent budget has been developed for the 2 meter aperture requirement. Under each mirror and the instrument port window error sources include fabrication, metrology, and mounting. Focus error contributors include despace, mirrors' distortion, focus increment/measurement accuracy, etc. Alignment error sources are decenter and dtilt, for a centered secondary. Detailed error budgets are contained in the respective subsystem descriptions in Section 4.

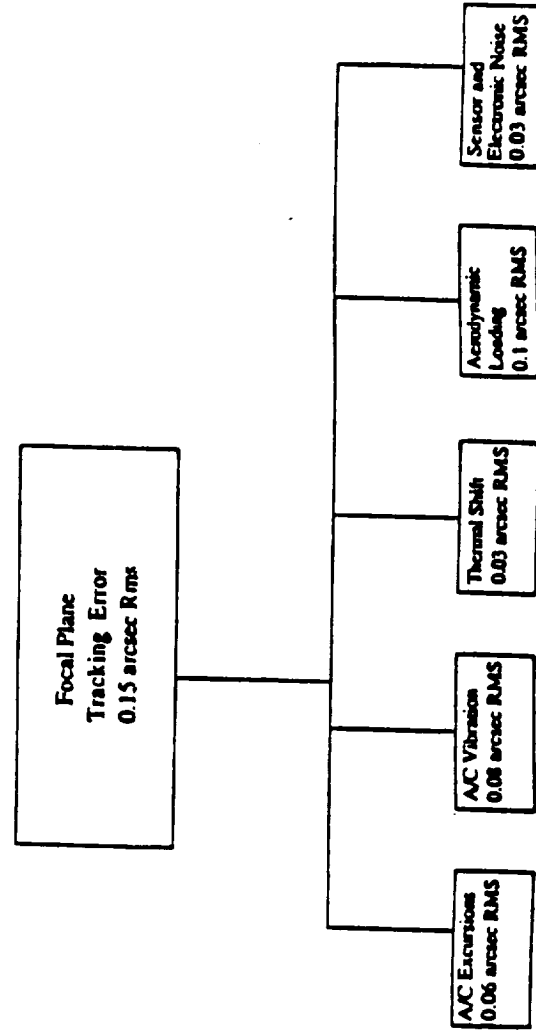
Under the overall tracking error requirement of 0.15 arcsec RMS, based on use of a focal plane tracking sensor, the contributors include: aircraft excursions, or gust/maneuver disturbance residual effects on the Telescope (due to air bearing "sticktion" or Telescope imbalance); aircraft vibration, or structure-borne vibration not attenuated by the vibration isolators and air bearing; thermal shift, which encompasses thermally induced relative motion between the focal plane tracking sensor and the instrument focal plane; aerodynamic loading, or wind-induced torques on the Telescope (major error source); and the omnipresent sensor and control system electronic noise.

### TRACKING AND WAVEFRONT ERROR BUDGETS

#### TELESCOPE WAVEFRONT ERROR BUDGET - 3 M APERTURE



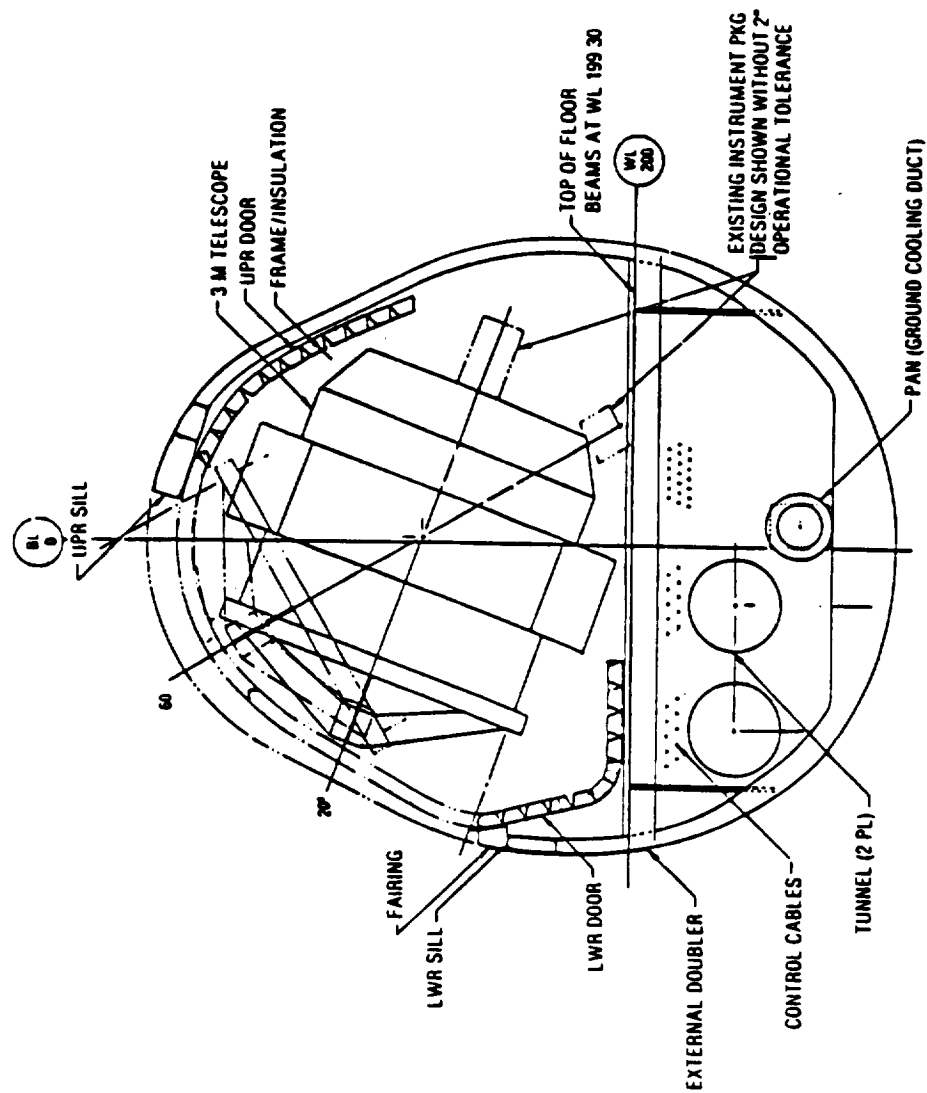
#### TRACKING SYSTEM ERROR BUDGET



### Telescope Volume/Geometry Constraint

The chart shows the current cavity geometry at the Telescope centerline position, as developed during the second phase of the Boeing Phase A cavity modification study. A representative model of the 3-meter Telescope, provided by ARC, is shown at its extreme elevation positions of 20° and 60° above horizontal. As can be seen, it appears that interference problems may arise at the 60° (full up) elevation position, if the Cassegrain instrument is not reduced in size. Also, the Telescope heading and secondary mirror mechanism are in close proximity to the cavity door. Note that this sketch depicts the Telescope with no cross-elevation/LOS offset; currently, Boeing believes that for this Telescope only  $\pm 2^\circ$  of these "coning" motions are allowable, while the current science requirement is for  $\pm 4^\circ$  (under review). Also, the specification calls for an elevation range of 15-75° with vignetting; the higher elevations may cause structural interference. Furthermore, the vibration isolation system "travel" (currently  $\pm 0.4$  inches during tracking, up to  $\pm 0.9$  inches for crash loads) expands the Telescope dynamic envelope directly. Having discovered the locations of potential interference, it is incumbent on the cavity designer to provide as much space as possible in these areas, and to a first level this has been done. Likewise, the Telescope detailed geometric design should be developed bearing these "stress points" in mind; otherwise the cross-elevation/LOS range, elevation range, and/or Telescope diameter must be reduced. Tradeoffs are continuing in these areas, and close coordination will be needed.

### TELESCOPE VOLUME/GEOMETRY CONSTRAINT



### Telescope Mass Budget and Status

The chart shows the mass budgets and status for the SOFIA Telescope, which is the physical element supported on the aft cavity bulkhead, including optical system and structure, air bearing and vibration isolation system, and counterweight/instrument flange. The original "going-in" budget was developed with an overall goal weight of 30,000 lbs, and reflected an early simplistic division of 10,000 lbs each for the Telescope, counterweight/instrument, and air bearing/vibration isolation system. The 30,000 lb goal was established to minimize the amount of ballast needed in the aft section of the aircraft for c.g. purposes, to balance both the Telescope and the added weight of the cavity modification. (Ballast is required for forward weights in excess of ~31,000 lbs at a ratio of about one pound ballast per 1.6 lbs forward weight; part of the "ballast" is taken up by aft-mounted mission equipment.) The current budget maintains the goal weight of 30,000 lbs, but has been redistributed to account for the known "exceedances" are in the air bearing and the counterweight, which are the main areas where improvement is possible with further definition. The counterweight, whose requirement is to balance the Telescope moment about the air bearing centerline, can be reduced greatly in mass by extending its length (arm) and distributing its mass in a "dumbbell" fashion. The aircraft configuration easily allows for this; instrument mounting issues would be a concern. No attempt has been made to lightweight the air bearing design as yet; this subsystem is a major candidate for further analysis and design iteration in the near term.

## TELESCOPE MASS BUDGET AND STATUS - LBS

ITEM	ORIGINAL BUDGET	CURRENT BUDGET	CURRENT STATUS
1. AIR BEARING	7,000	13,500	17,900
2. VIBRATION ISOLATION SYSTEM	3,000	550	550
3. INSTRUMENT/COUNTERWEIGHT (INCL. GYROS)	10,000	6,900	8,500
4. TELESCOPE (OPTICS) STRUCTURE	3,850	250	200
5. CENTERPIECE SUPPORT STRUCTURE	2,000	5,600	5,600
6. PRIMARY MIRROR	1,500	1,500	1,680
7. PRIMARY MIRROR MOUNT AND COOLING	1,500	1,000	1,200
8. SECONDARY MIRROR	100	100	100
9. SPIDER/HEADRING	450	350	350
10. CHOPPER MECHANISM	100	100	100
11. CAMERAS (TRACKER, ACQ.)	500	150	150
TOTAL	30,000	30,000	36,310

### SOFIA Payload Mass Budget

The SOFIA-assigned payload mass budget is shown; this represents the mass of all personnel and equipment needed for SOFIA science missions and ferry flights, which is added to a "stripped" aircraft to obtain total Observatory mass. The cavity modification study contractor, BMAC, has taken the further step of defining the "stripped" aircraft empty weight, the equipment locations (layout) for c.g. and ballast calculations, fuel requirements, drag increments, etc., to determine the SOFIA aircraft performance capabilities.

The weight of the cavity modification has grown from 12,700 lbs due to upsizing the baseline telescope from 2.5 to 3.0 meters (primary mirror diameter) in the Phase II study, necessitating a larger cavity opening and, hence, greater structural reinforcement. Possible areas for weight reduction are under consideration. The ballast required for this configuration is "dead weight" to be added in the tail area; some ballast is accounted for by aft-mounted mission equipment, including consoles, nitrogen tanks, compressors, etc. Ultimately it is desirable to achieve a science mission payload of 60,000 lbs or less, in order to meet the standard aircraft endurance at altitude requirements; the alternatives are to incorporate "enhanced performance" or boosted thrust engines, and/or reduce the modification drag increment. Capability in the current configuration is ~ 5.5 hours at FL410. Further details of aircraft weight and performance are provided in Section 5.

### SOFIA PAYLOAD MASS BUDGET

ITEM	MASS. LB
1. TELESCOPE SYSTEM (TELESCOPE, INSTRUMENT/ COUNTERWEIGHT, VIBR. ISOL. SYSTEM/AIR BEARING)	30,000
2. CAVITY MODIFICATION (BULKHEADS, DOOR, BLC, ETC.)	16,000
3. PNEUMATIC SYSTEM	2,000
4. NITROGEN SYSTEM	1,500
5. DATA ACQUISITION/MANAGEMENT SYSTEM AND INTERFACE	1,750
6. CONTROL CONSOLES/EQUIPMENT RACKS	3,000
7. VACUUM SYSTEM	700
8. CAVITY ENVIRONMENTAL CONTROL SYSTEM	750
9. AFT GALLEY	1,500
10. CREW AND PASSENGERS	1,800
11. SAFETY EQUIPMENT	1,000
12. SEATS (40)	1,000
13. AFT LAVATORY	385
14. FOOD AND WATER	400
15. BALLAST	10,020
TOTAL PAYLOAD:	<u>71,805</u>
FERRY FLIGHT: ADD: 31 PASSENGERS	6,200
MISC. CARGO	<u>46,520</u>
	52,720
	(TOTAL 124,525)

### 3.4

#### Top-Level Interfaces

For purposes of this early "concept definition" phase of the SOFIA program, major interfaces have been defined only in a broad sense. Efforts to specify detailed interface locations and requirements are needed in the near term to identify task allocation, element scopes and boundaries, and detailed configuration and performance "sub-requirements." It is useful for now to identify interfaces only between the major elements shown, which are: the Aircraft System (including the cavity and its subsystems); the Telescope Assembly (with peripheral equipment and science instrument); the Consoles and Electronics Subsystem; and the Ground Support System (facilities and equipment). Interfaces fall generally into the discipline categories shown, and the matrix defines which categories apply across the various boundaries (top-level).

Structural/mechanical interfaces between the Telescope Assembly and Aircraft are the bulkhead/vibration isolation mount and power/communications line routing from cavity to Telescope; thermal/environmental is conduction and radiation/convection between the cavity and Telescope.

Between the Aircraft and Consoles and Electronics are: structural - equipment mounting and cable/line routing; thermal/ environmental - on board cavity cooling/heating/purging, cabin environment and (potentially) equipment cooling; electrical - power distribution to consoles, computers, etc.; and communications between aircraft based sensors (navigation, air data autopilot, etc.) and mission equipment.

Between Aircraft and Ground are: structural - ground equipment (cooling, electrical, etc.) attachment to aircraft; environmental - cooling equipment to cavity; and electrical - GSE to aircraft (power cart).

Between Telescope and Consoles and Electronics are: environmental - primary mirror cooling/heating and instrument environment; electrical, from the console power supplies to the Telescope Assembly components; communications, control and monitor (see next page). Between Telescope and ground is structural/mechanical only (Telescope, P.M., handling equipment). Between Science/Mission and Ground is communication only (Ground Station Link).

### MAJOR INTERFACES

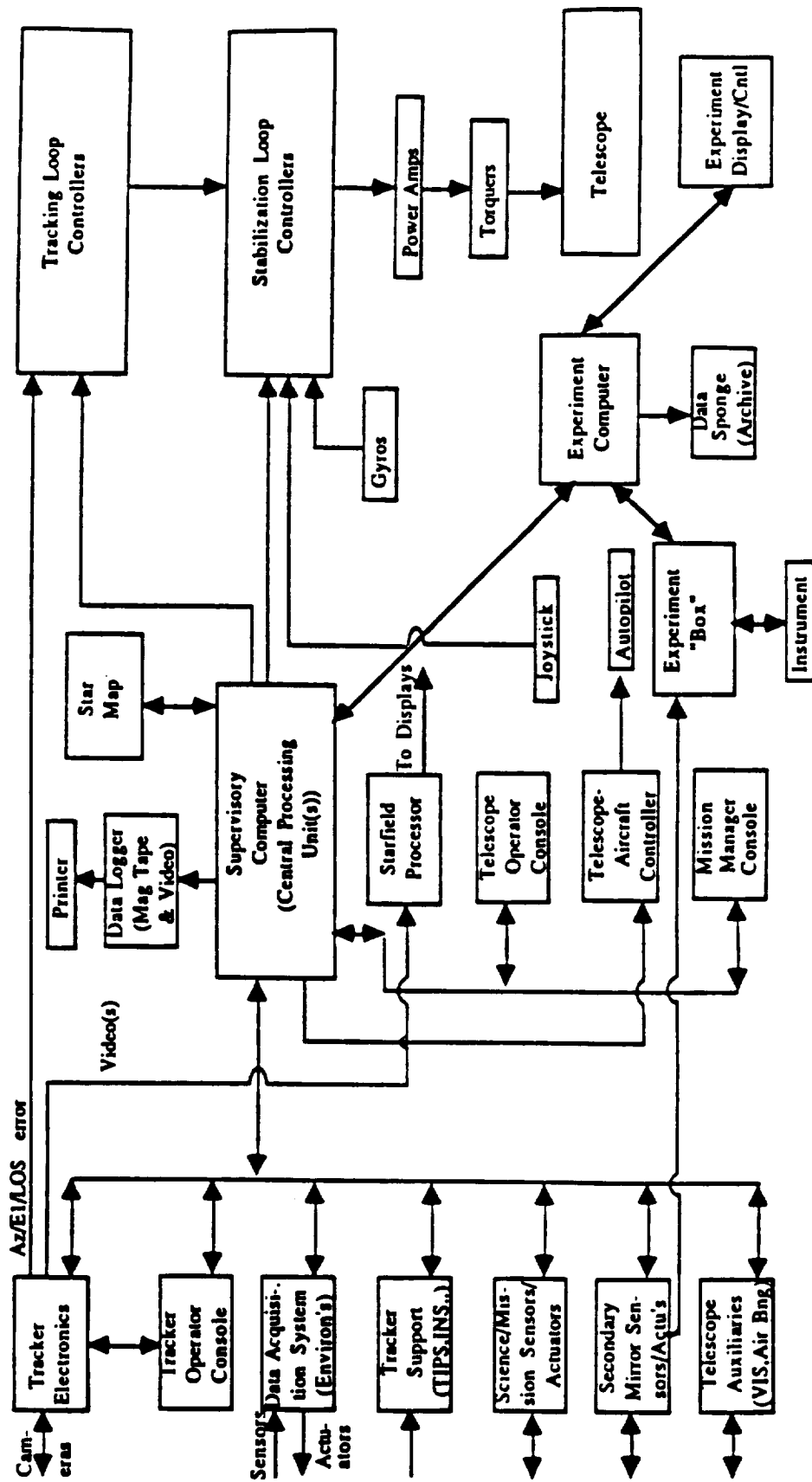
- ELEMENTS
  - AIRCRAFT SYSTEM
  - TELESCOPE ASSEMBLY
  - CONSOLES AND ELECTRONICS SUBSYSTEM
  - GROUND SUPPORT SYSTEM
- INTERFACES
  - STRUCTURAL/MECHANICAL ①
  - THERMAL/ENVIRONMENTAL ②
  - ELECTRICAL POWER ③
  - COMMUNICATIONS AND CONTROL/MONITOR ④
- INTERFACE MATRIX

	AIRCRAFT	TELESCOPE	CONSOLES/ ELECTRONICS	GROUND
AIRCRAFT	X	① ②	① ② ③ ④	① ② ③
TELESCOPE		X	② ③ ④	①
CONSOLES/ ELECTRONICS			X	④
GROUND				X

### Control and Monitor Communications Interfaces

This top-level communications block diagram, which connects elements of the Telescope, Data Management/Acquisition and Control, and Aircraft systems, depicts the complex interactions involved in mission operations with SOFIA. All of the subelements except the direct tracking/guiding loop interface through the Supervisory Computer (redundant Central Processing Unit), which lies at the heart of the system. The system is modeled to some extent after the KAO, but the centralized network architecture updates the more distributed KAO system; this allows use of modern Local Area Network technology. Another central node is the Experiment Computer, which interfaces with experimenter main and remote workstations, data archive, the system CPU, and the instrument via the experiment electronics "box." The latter has a direct path to the secondary mirror chopper, enabling chop phase control. Environmental and Science/Mission sensor/actuator signals (e.g., for cavity environment, door/fence and experiment control) are routed through the CPU to telescope operator, mission manager, and experimenter workstations. The tracker operator has separated controls for initial target acquisition, and manual on-axis and offset guiding operations; real time starfield video signals from the tracker are also routed to telescope operator and experimenter displays. Aircraft avionics (air data and inertial navigation systems) provide inputs through the CPU for recording and monitoring, and a tracking control signal is routed to the aircraft autopilot for steering commands to keep the Telescope within its cross-elevation range. Peripherals to the CPU include a computer generated starfield map for planned targets, a data logger and printer.

### TOP-LEVEL COMMUNICATIONS INTERFACES



### 3.5

#### Summary and Conclusions

The goals of the SOFIA in-house Phase A study have essentially been achieved, with the establishment of basic feasibility and preliminary cost estimates for the aircraft modification, Telescope System, and mission operations and ground support systems. The BMAc Phase II concept definition study, completed in August 1987, has developed the cavity, cavity door, BLC fence/ramp, aircraft layout, systems routing, and other technical concepts in sufficient detail to allow confidence in feasibility assessment and costing. With the exception of some areas of technology yet to be demonstrated, but believed to be tractable, the Telescope System concept has also been shown to be feasible; alternative approaches have been identified where technical risk still exists. The mission operations and ground support systems can be developed with minimum risk, using commercial or off-the-shelf elements in many areas. Cost assessments have been performed for the above major areas, using computer cost models, contractor estimates (e.g., BMAc, Corning/Kodak), and contracted cost estimating efforts (e.g., SAIC). These estimates are not included with this report. Finally, many areas of potential risk have been identified, as delineated in the following pages and in the subsystem descriptions of Section 4. The top-level system issues are believed to be: Telescope System mass, affecting aircraft performance; telescope optics technology, performance and mass, particularly the primary mirror, against the stringent image quality requirements; and the telescope pointing performance, with loads undefined in some areas, against the difficult pointing stability requirements, also affecting image quality. Work is ongoing to further develop and assess concepts in these areas.

### **SUMMARY AND CONCLUSIONS**

- BASIC FEASIBILITY ESTABLISHED
  - AIRCRAFT MODIFICATION - TECHNICAL AND COST
  - TELESCOPE SYSTEM - WITH MODERATE TECHNICAL RISK AREAS
  - OPERATIONS AND GROUND SUPPORT SYSTEMS - BASICALLY KAO UPGRADES
- COST ASSESSMENT
  - AIRCRAFT MODIFICATION
  - TELESCOPE SYSTEM
  - GROUND SUPPORT AND FACILITIES (C OF F)
- MAJOR RISK AREAS IDENTIFIED
  - TELESCOPE SYSTEM MASS
  - OPTICS PERFORMANCE AND TECHNOLOGY
  - POINTING PERFORMANCE

## Issues and Concerns

Having established basic feasibility and preliminary cost estimates for the SOFIA concept developed in this Phase A study, it is necessary for the Project to identify those areas where significant technical risk threatens the ability of the Observatory to meet its requirements, as defined by the SOFIA Science Consulting Group. Elements needing further definition or technology development are identified on the charts, and fall into the Telescope and Aircraft System categories; no major concerns have been identified for the Science/Mission Operations System or the Ground Support System. A potential threat to the aircraft performance requirements (observing time at altitude) is the Telescope System mass, where the 30,000 lb goal for a 3-meter telescope currently has no margin. The system mass must be traded against size, stiffness and dimensional stability requirements, impacting image quality and sensitivity. In the optics area, it is clear that polishing technology for a 3 m,  $f/1$  primary mirror (with its derived wavefront error requirements) has not been demonstrated. A potential trade is study of larger  $f$  numbers (e.g.,  $f/2$ ) for the primary, with corresponding larger secondary mirrors, impacting sensitivity. The primary mirror weight, although theoretically close to its 1500 lb budget (reflector "areal density" of  $\sim 110 \text{ kg/m}^2$ ) has also not been demonstrated, with concerns for the structural aspects of the mirror and mount being paramount. All of these factors (and the cavity volume constraints) indicate further study of achievable collecting area is necessary; certainly an aperture in the 2.7 m range should be feasible. Other concerns against image quality requirements are the extremely tight derived structural and optical tolerances; the current concept requires system refocussing with temperature changes as small as 2 degrees F. This may be an unacceptable operational handicap, impacting observing efficiency. A major technology concern is also apparent in the scaled-up air bearing concept, which requires an air gap less than 1/1000 inch for a 48-inch diameter rotor; dimensional tolerance, thermal gradient, and pressure differential requirements are important concerns for which an air bearing technology development/hardware demonstration effort is probably warranted. The air bearing weight is also a system issue; although its budget has grown, it still needs "lightweighting" to meet the goal. The stringent telescope pointing stability requirement (0.15 arcsec), corresponding to the image quality requirements, is another major concern in the flight environment. Many of the forcing functions are still largely unknown, including telescope wind loading, potential air bearing "stiction," wire bundle loads, cavity acoustic resonances, etc. A wind tunnel test program is needed to investigate several of these areas, and to study "seeing" effects and incremental drag. A potential trade is the inclusion of image motion compensation (IMC) by dithering the secondary or tertiary mirror; however, high frequency jitter sensing is a major concern for IMC. Another tradeoff resulting from the cavity volume constraint is that of telescope size vs cross-elevation/LOS angular range; apparently one parameter or the other (3 m,  $\pm 5^\circ$ ) must be alleviated. A final concern dealing with the telescope and cavity is the need to verify the results of the thermal models developed for SOFIA; one possible method would be to predict and verify KAO performance using similar models and assumptions.

### **ISSUES AND CONCERNS**

- TELESCOPE SYSTEM
  - SYSTEM MASS (VS. STIFFNESS, DIMENSIONAL STABILITY, SIZE AND AIRCRAFT PERFORMANCE)
  - PRIMARY MIRROR POLISHING (VS. LARGER  $f$ /RATIO, RELAXED IMAGE QUALITY)
  - PRIMARY MIRROR MASS/"AREAL DENSITY" (VS. SIZE, STRUCTURE AND MOUNT DESIGNS)
  - STRUCTURAL/OPTICAL TOLERANCES FOR IMAGE QUALITY
  - AIR BEARING DESIGN AND MASS (NOT DEMONSTRATED)
  - POINTING STABILITY IN FLIGHT ENVIRONMENT (UNKNOWN LOADS)
  - CROSS ELEVATION/LOS ANGULAR RANGE (CAVITY VOLUME CONSTRAINT)
  - CAVITY/TELESCOPE THERMAL MODEL - VERIFICATION

G-2

### Issues and Concerns (Contd)

For the aircraft modification study, three areas of important concern are currently identified: cavity/structural mass, incremental drag and "seeing" impacts. A tradeoff study is warranted for the bulkhead mass vs. deflection due to differential pressure; mass can be reduced if deflection is allowed to increase, but concerns are raised for bulkhead/telescope interface dimensional tolerances and for design of the telescope capture/locking device, which might have to be moved from the forward cavity bulkhead elsewhere (e.g., aft bulkhead). The incremental drag due to cavity door/aircraft skin geometry (climb performance with door closed), and due to BLC fence deployment (impacting cruise ceiling while observing) is an issue requiring further modeling and test. Of course, seeing effects from boundary layer control devices are a continuing concern.

Finally, certain "project issues" have been identified requiring near-term review. First, a more complete, detailed and clear statement of system requirements is needed for future program phases, with efforts having been initiated in this area. One general item to be addressed is to what extent design requirements (vs. purely performance requirements) are to be levied; that is, the configuration "trade space" might have to be opened. Another effort which should be undertaken as part of the requirements review is asserting a "project position" against difficult requirements; that is, the project would establish alternate (relaxed) requirements in certain areas to reduce technical, schedule and cost risks, particularly in the image quality and pointing stability areas. A final programmatic subject for which near-term guidance is warranted is the definition of subsystem/interface boundaries, work allocation, and responsibilities for design, development, integration and testing of the various SOFIA elements. This impacts the scope of effort required of NASA/ARC, the telescope contractor, and the aircraft modification contractor. Efforts have also been initiated in this area.

### **ISSUES AND CONCERNS (CONTD)**

- AIRCRAFT SYSTEM
  - INCREMENTAL DRAG (CLOSED DOOR AND DEPLOYED BLC FENCE, VS A/C PERFORMANCE)
  - ALLOWABLE BULKHEAD DEFLECTION (VS. MASS)
  - CAVITY "SEEING" AND SHEAR LAYER CONTROL DEVICES
- PROJECT ISSUES
  - DEVELOPMENT OF MORE COMPLETE AND DETAILED REQUIREMENTS
  - CONSIDERATION OF RELAXED REQUIREMENTS
  - DEFINITION OF SYSTEM/SUBSYSTEM BOUNDARIES, WORK ALLOCATION, AND RESPONSIBILITIES







## **SECTION 4**

### **TELESCOPE SUBSYSTEMS DESCRIPTION**

- 4.1 Optics**
- 4.2 Telescope Structure**
- 4.3 Air Bearing and Vibration Isolation System**
- 4.4 Pointing and Control Subsystem**
- 4.5 Data Management, Acquisition, and Communications**
- 4.6 Telescope and Cavity Thermal Model**
- 4.7 Instrument Accommodations**

#### 4.1

### Optics

#### Major Optical Requirements of the Telescope

The aperture of the telescope is to be in the range of 2.5 to 3.0 m. The minimum requirement of 2.5 m is set by the objectives of the scientific mission for sensitivity and resolution. The upper limit will be set by the size of the aircraft. Presently, the Boeing 747 SP appears capable of accommodating close to 3 m.

The spectral or wavelength range over which the telescope will operate must be very wide to accommodate the needs of the scientific observations and pointing control. Short wavelength observations of the planets plus a need for visible fine guidance through the telescope itself dictate imaging in the visible to near UV. Observations at the much longer millimeter wavelengths are also desired.

The configuration will be of a Cassegrain type to provide the compactness needed to contain the telescope within the aircraft and the aerodynamic boundary of the open cavity.

The unvignetted field over which the image quality specification must be met is defined over a circle which is 8 arc minutes in diameter at an  $f$ /ratio of 18. This ensures that baffles and apertures do not intercept any part of the beam within this field when operating at the largest system  $f$ /ratio.

The  $f$ /ratios which the telescope will provide depend upon the configuration that is desired for the scientific instrument. For instruments that operate at the Cassegrain focus, an  $f/11$  beam is provided. For instruments that operate inside the pressurized cabin a Nasmyth focus is provided. The focus location is available at two places corresponding to a system  $f$ /ratio of either  $f/13.5$  or  $f/17$ , depending on the needs of the specific instrument, by providing two different secondary mirrors.

For photometric reasons, it is useful to define the requirements for imaging in terms of encircled energy at a specified wavelength. It is also useful to specify image quality over an aperture in the event that the primary mirror surface errors are greater in the outer zones, due to the difficulty in fabrication or mounting. The effects of atmospheric seeing are included separately in a system-level image quality budget.

The primary mirror coating has a reflectivity that is nearly flat over the spectrum. Bare, vacuum-deposited aluminum is very good in this respect, in addition to having a high visible reflectivity and excellent durability in the expected environment and for cleaning.

The focus locations accommodate scientific instruments at the Cassegrain focus, or at the Nasmyth focus where the instrument may be accessed by personnel in the pressurized cabin.

### MAJOR OPTICAL REQUIREMENTS OF THE TELESCOPE

- PRIMARY MIRROR DIAMETER:  $\geq 2.5\text{M}$  (3.0M GOAL)
- SPECTRAL RANGE:  $0.3\mu\text{M} < \lambda < 1600\mu\text{M}$
- CONFIGURATION: GENERIC CASSEGRAIN, PROVISION FOR CASSEGRAIN OR NASMYTH FOCUS
- FIELD OF VIEW: 8 ARCMIN UNVIGNETTED
- SYSTEM F/RATIO:
  - F/11: CASSEGRAIN
  - F/11-18: NASMYTH (ACCOMMODATED USING DIFFERENT SECONDARIES)
  - F/13.5 & F/17: NASMYTH (STANDARD SECONDARIES)
- IMAGE QUALITY
  - VISIBLE:  $\leq 1$  ARCSEC DIA. ENCIRCLES 80% OF ENERGY IN IMAGE OF A POINT SOURCE ON AXIS AT  $0.5\mu\text{M}$  USING THE CENTRAL 2M APERTURE.
  - $\leq 3$  ARCSEC WITH 3M APERTURE
- PRIMARY MIRROR COATING: BARE ALUMINUM
- FOCUS LOCATION:
  - CASSEGRAIN: 40 CM BEHIND THE PRIMARY MIRROR SUPPORT PLATE.
  - NASMYTH: AFT OF THE AIR BEARING CENTERLINE.
  - BETWEEN TELESCOPE AND AIR BEARING WITH SPECIAL FITTINGS

### Telescope Configuration

The SOFIA telescope is shown oriented vertically. Incoming light is focused toward the prime focus. It is refocused by the secondary mirror to the Cassegrain focus, or the Nasmyth focus via the tertiary mirror, depending upon the choice of secondaries that has been made. In the event the Cassegrain focus is chosen the tertiary mirror would be removed or replaced with a beamsplitter if visible fine guiding were desired.

The primary mirror baselined for this study will be of a light weight, sandwich-type construction. Its weight is desired to be no more than 1500 lb, based on system-level weight budgeting.

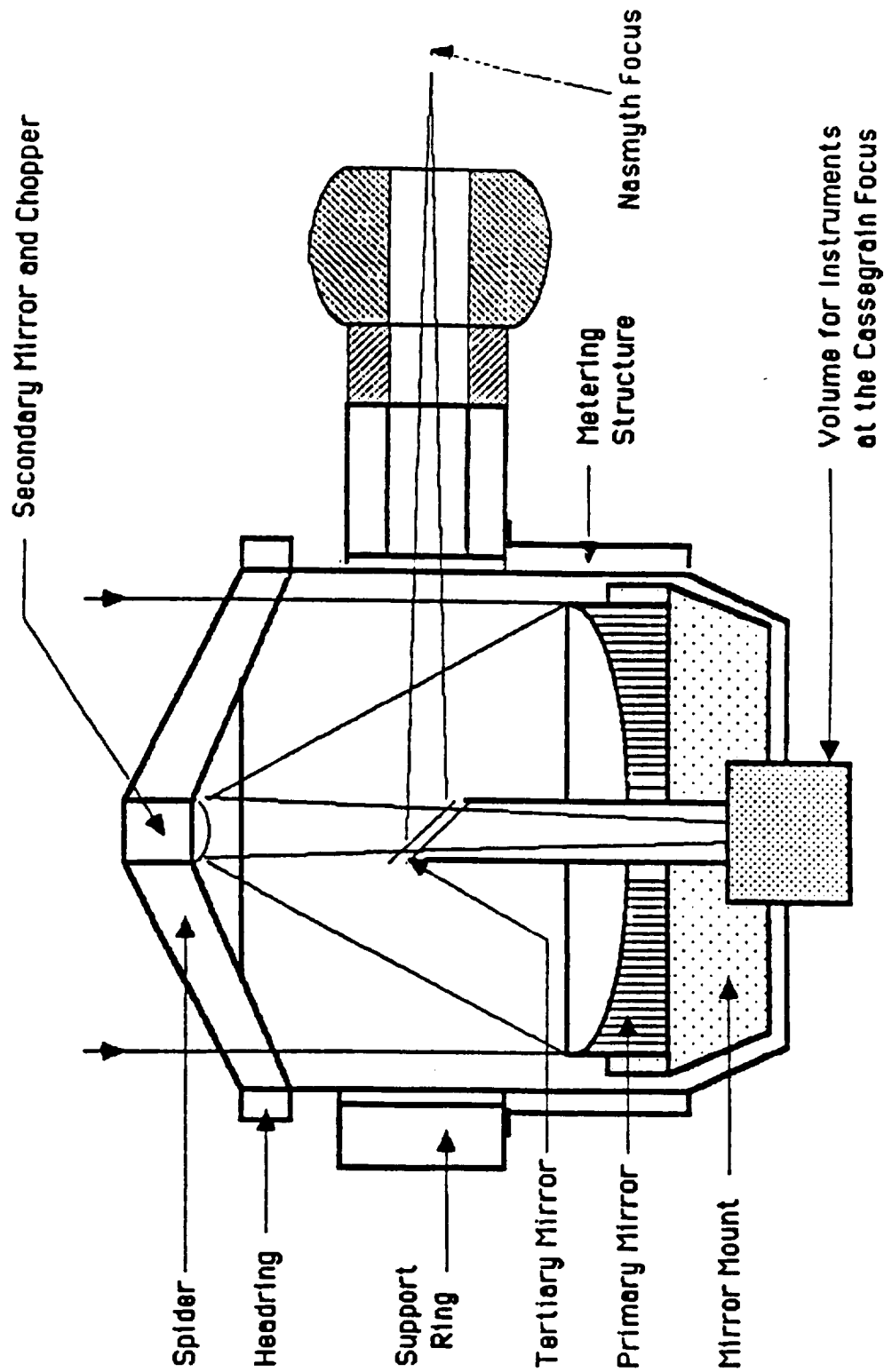
The secondary mirror is mounted on a space-chopping mechanism. The mechanism oscillates the secondary to achieve an alternating view of the sky when background subtraction signal processing is to be employed. The mechanism will also make it possible to move the secondary axially to adjust the telescope focus when dictated by large temperature changes, and to provide a "focus dither" function for submillimeter astronomy.

The secondary mechanism is supported in a housing by the spider which is in turn attached to the heading. The heading couples the metering structure to the spiders, and provides support to a boresighted star tracker and balance weights if required.

The telescope is attached to the telescope support ring and then to the spherical air bearing by a tubular structure.

A graphite-epoxy tube is utilized as a metering structure in the baseline design. Its purpose is to limit the thermally induced changes in spacing between the primary and secondary mirror, and keep de-center and de-tilt relative motions within limits prescribed by the system error budget.

## TELESCOPE CONFIGURATION



### Optical Design Trade-offs

The chief parameter of the SOFIA telescope which is not fixed by the requirements, and therefore adjustable according to trade-off considerations, is the conic constant of the primary mirror. There are three principle options: a paraboloidal surface, in which case the telescope is a classical Cassegrain; a slightly hyperboloidal surface chosen so that for one of the focal ratios the telescope will be an aplanatic (Ritchey-Chretien); and a more hyperboloidal surface chosen so that for one of the focal ratios the telescope will be coma-compensated.

These options are detailed in the accompanying table. The table presents the three design categories mentioned above. Within two of the categories, the Ritchey-Chretien and the coma-compensated, two subordinate options are given, differing in the matter of which system focal ratio is optimized. The first row of numbers is the primary mirror conic constant. There are two systems in common use for defining conic constant. In the one adopted here the value "-1" represents a perfect paraboloidal surface. The slightly more negative values indicate hyperboloidal surfaces (the more negative, the more strongly hyperboloidal.)

Since, regardless of the primary mirror surface choice, the telescope will be operated at varying system focal ratios, each of the five columns for different primary mirrors is further subdivided into two columns each. These are for the two standard system focal ratios of 13.5 and 17.0, which will be obtained by use of either of the two supplied secondary mirrors. (Focal ratios from  $f/11$  to  $f/18$  will be feasible should appropriate secondary mirrors be available.) The next row of numbers gives the secondary mirror conic constant, determined so as to correct spherical aberration. (Spherical aberration is the first to be corrected in nearly all telescope designs since it affects the image size on axis. The other low order aberrations affect only the image quality for off-axis objects, or when the secondary mirror is tilted.)

The final two rows of numbers give the third order coma coefficients with respect to field angle and with respect to secondary tilt angle. This is the lowest order for which coma exists. In each case the size of the effect on the image of a point source is proportional to the respective angle. The coefficients are the constants of proportionality. As can be seen, there is a choice between eliminating coma as a function of field, and eliminating it as a function of tilt. As can also be seen, it is relatively unimportant which system focal ratio the primary mirror would be optimized for, and the difference between the classical Cassegrain (paraboloidal primary) and Ritchey-Chretien (aplanatic) design is small compared to the difference between these and the coma-compensated design.

## COMA COEFFICIENTS FOR VARIOUS DESIGNS

Design	paraboloidal	Ritchey-Chrétien			coma-compensated		
Prim mir conic cons	-1.000000	-1.000769	-1.001219	-1.111496	-1.111721		
System focal ratio	13.5 17.0 13.5 17.0	13.5 17.0 13.5 17.0	13.5 17.0 13.5 17.0	13.5 17.0 13.5 17.0	13.5 17.0	13.5 17.0	
Sec mir conic cons	-1.346 -1.266 -1.355 -1.275	-1.361 -1.280 -2.750 -2.603	-2.753 -2.750 -2.603 -2.753	-2.753 -2.606			
Field coma coeff	.00103 .00065 .00038 .00000	.00000 .00038 .09305 .09324	.09305 .09324 .09305 .09324	.09305 .09324 .09305 .09324	.09324 .09362	.00019 .00000 .00019	
Tilt coma coeff	.09426 .09407	.09362 .09343	.09324 .09305	.00019 .00000	.00019		

Conic constants are given in the system in which 0 represent a sphere and -1 a paraboloid.

Coma coefficients are ratio of point image angular size in astronomical space to field shift angle in astronomical space.

### Optical Design Tradeoffs (cont'd)

Concern for the "third-order field coma coefficient" of the telescope optical design results from its affect on the field of view.

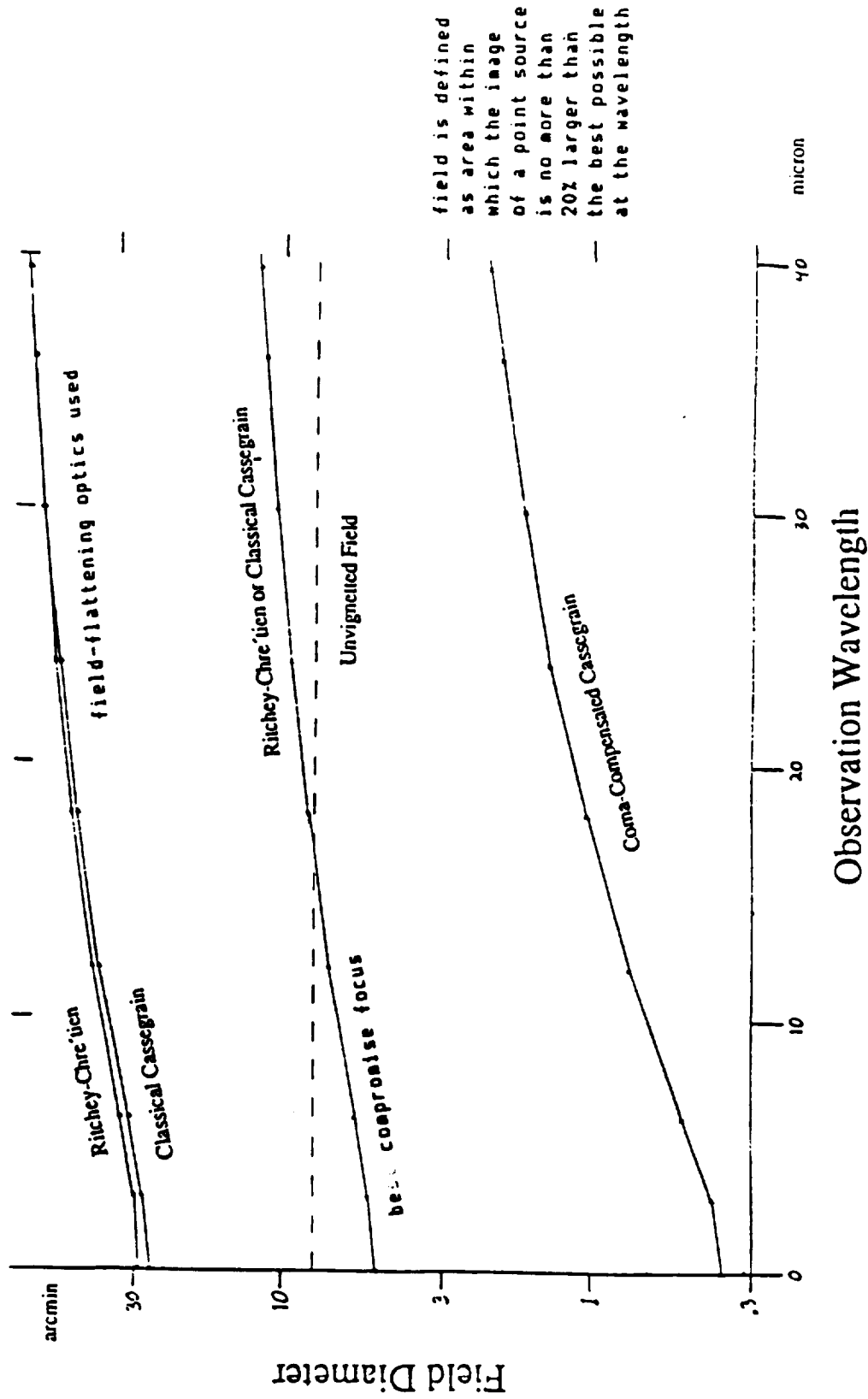
There are two general categories of design considerations in regard to the field of view. The first is "vignetting". This is a purely geometrical consideration of whether structural surfaces interfere with the beam of light. SOFIA is specified to have an 8 arcminute unvignetted field of view, which means that for any celestial object within 4 arcminutes of the line-of-sight of the telescope no surface or mirror edge, except the edge of the secondary mirror which has been chosen as the aperture stop, will limit the light reaching the focal plane image.

The other category is aberrations. In theory a telescope can only produce a perfect image at the center of its field of view. (In practice, of course, not even this is possible.) The image quality at an angle from the line-of-sight is always worse than the best image achievable along the line-of-sight. As a result only some small area around the line-of-sight is used in practice. In different designs different aberrations may be the first to unacceptably reduce the image quality. Furthermore, the acceptable image quality depends on the wavelength of observation. This is because "diffraction", which is directly proportional to wavelength, also contributes to the image, and for longer wavelengths will obscure more and more aberration.

The accompanying graph shows field-of-view as a function of wavelength for the designs under consideration for SOFIA. Field coma controls the field of view for the coma-compensated design. For the paraboloidal and aplanatic designs the first limiting aberration is "curvature of field," which makes it difficult to bring the entire field to focus simultaneously on a flat detector. It is possible to adopt a "best compromise focus", in which a circle intermediate between the center point and the edge of the field is brought into focus. Were it possible to use a curved detector, or additional optical element to flatten the field, astigmatism and field coma would limit the field of view in these two designs. In this case the advantage of the Ritchey-Chretien begins to be seen.

It is not necessary to choose the primary mirror conic constant yet, but on the basis of present analysis it would seem the coma-compensated design should be rejected, and the slightly easier paraboloidal primary is as adequate as the aplanatic.

### UNIFORM QUALITY FIELD OF VIEW VERSUS WAVELENGTH



## Optical Layout

The layout of the SOFIA telescope is most strongly constrained by the need to fit within the aircraft cavity. An additional constraint is the limit on the size of the secondary mirror placed by the need to chop it.

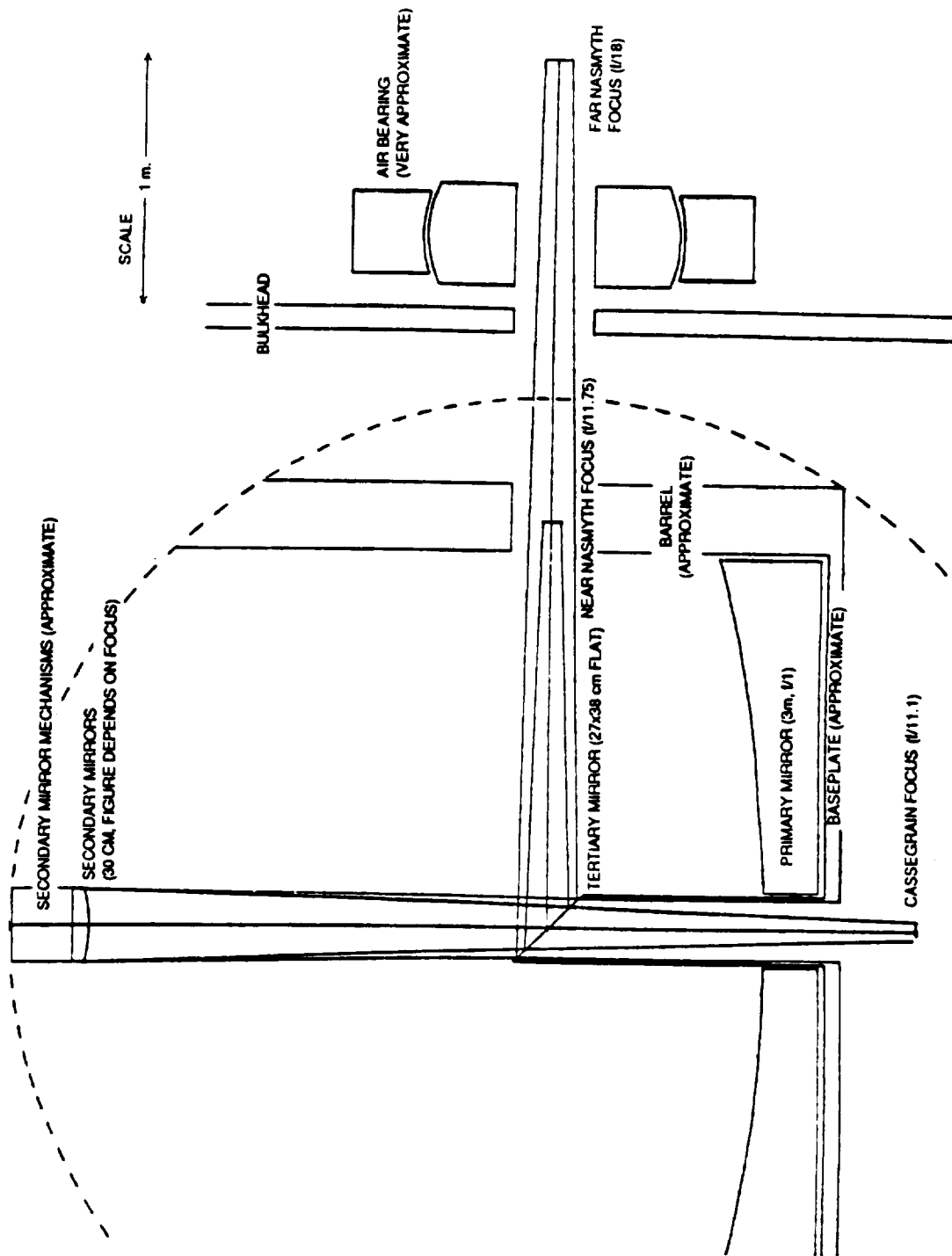
Within these constraints it is desirable for the primary mirror to be as large as possible, to increase observational efficiency, and for the primary mirror focal length to be as long as possible to reduce aberrations and ease mechanical tolerances. It has not been possible to make absolute determinations of these limits. Instead a rough estimate of a 3m clear aperture and a 3m focal length have been assumed. It has been verified that under reasonable estimates of other related parameters, such a telescope will fit in the cavity. In particular, assumptions have been made concerning the length of the secondary mirror mechanism, thickness of the primary mirror, and thickness of the telescope structure surrounding the primary mirror. We have used 30cm as the allowed secondary mirror clear aperture.

The secondary mirror is positioned with respect to the primary mirror so as to fill the cone from the primary mirror to the prime focus. In the final design it will be moved slightly closer, so as to guarantee it functions as the system aperture stop for all points within the desired unvignetted field of view and regardless of tilt within the specified limits. This will also reduce the system aperture slightly below the primary mirror clear aperture.

The rotation of the telescope to different elevations determines the ideal position of the pivot line (line through the center of the spherical air bearing parallel to the long axis of the aircraft). Ideally, for geometrical considerations, the point at which the pivot line intersects the central axis of the telescope will be at the center of a circle which is touched by the farthest points of the telescope, namely the top of the secondary mirror mechanism and the outermost edges, just below the base of the primary mirror, of the telescope structure. The center of the tertiary mirror is conveniently placed at this same point, though the tertiary position could be somewhat different since there is no need for the optical beam to pass exactly through the center of the air bearing.

With the selection of a single size for the secondary mirror, the position of the Nasmyth system focus becomes a function of the system focal ratio in use. The faster the system, the closer the focus to the telescope axis, and the slower the system, the further the focus from the axis. It is possible that this may lead to restrictions on the focal ratios available at the Nasmyth focus. The ratios available at the Cassegrain focus will be even more restricted, and smaller (faster) than at the Nasmyth. In either case telecompression or extension could be used to alter the focal ratio if a suitable lens material is available for the wavelength range to be used. This would in general depend on the instrument.

### SOFIA FIRST-ORDER OPTICAL DESIGN



## Optical Prescription

System type: SOFIA is planned to be a Cassegrain/Nasmyth telescope. This means it will have a large concave primary mirror, a small convex secondary mirror placed between the primary mirror and its focal point, and a removable flat tertiary mirror between the primary and secondary mirrors at a 45 degree angle.

Aperture stop: Because the telescope will not be cryogenically cooled, it will "glow" at infrared wavelengths. To limit the interference of this glow on astronomical observations the system aperture stop will be at the secondary mirror. This is sometimes referred to as "undersizing the secondary."

Active secondary: The secondary mirror will be articulating. This will allow "chopped" observation, in which the instrument alternately sees the target and blank sky, and fine adjustment of the effective pointing direction (e.g., for scans).

Primary Mirror: SOFIA is planned to have a primary mirror with up to a three meter usable diameter. The useful astronomical aperture will be slightly less than this, to allow for the unvignetted field of view and chopping with the aperture stop at the secondary mirror. The exact value is a function of the secondary mirror in use.

System focal ratios: The secondary mirror and its support structure will be removable and replaceable. This will allow observation at varying focal ratios. Two secondary mirrors will be supplied, one for operation at  $f/13.5$  and one at  $f/17$ . The system will be capable of accommodating focal ratios from  $f/11$  to  $f/18$ .

### SOFIA OPTICAL PRESCRIPTION

Element	Separation f/13.5 f/17	Diameter	Quality	Focal Length f/13.5 f/17	Conic Constant
Primary mirror		3000mm - 300mm	.06urms	3000mm	-1.0000
	2700mm				
Secondary mirror		300mm - 22mm	.03urms	324mm 319mm	-1.3456 -1.2656
	1780mm				
Tertiary mirror		300mm x 400mm	.03urms		
	2270mm 3320mm				
Focal plane		120mm			

"Diameters" are outer and inner for primary and secondary, minor and major for tertiary.

## Image Quality Analysis

In operation the image quality of a telescope varies as a function of the operating wavelength, with position within the field of view, and, for telescopes which have a tiltable secondary, with the amount of tilt. These variations are determined from diffraction theory and by the design, as previously discussed. In addition a telescope can be characterized by its best achievable image quality, for its shortest operating wavelength, in the center of the field, with the secondary untilted. This depends on the manufacturing and operating tolerances of the telescope optics and structure, and on seeing conditions.

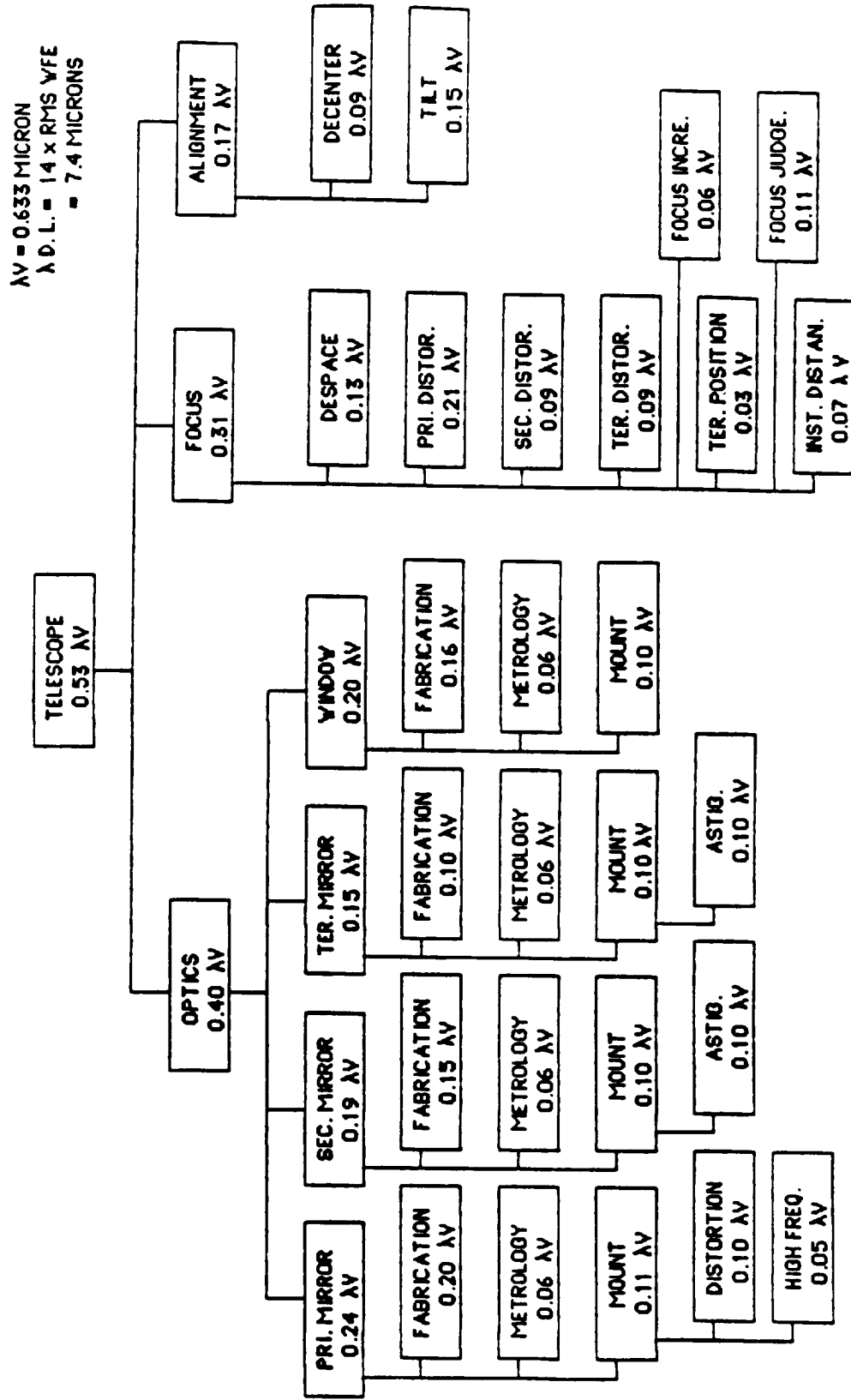
For specification and analysis purposes requirements were established for the seeing, and for the telescope. The latter was fixed at .5 micron operating wavelength, in the center of the field with the secondary untilted. Both were defined in terms of the diameter, in astronomical object space, of a circle which would enclose 80 percent of the energy from a point source. A visible wavelength, rather than an infrared wavelength, was chosen for the image quality criterion, because of the need for fine guidance from the focal plane image.

In view of the lack of precedent for a 3 meter class  $f/1$  primary mirror, it was noted that the central 2 meter diameter portion is equivalent to an  $f/1.5$  mirror, for which there are polishing precedents. Therefore optimum performance was demanded only when the primary mirror is stopped down to a 2 meter sub-aperture. Specifically a 1 arcsecond image (diameter of circle enclosing 80 percent of a point source energy) is required of the telescope in this circumstance. A 3 arcsecond image is demanded for the full aperture. In addition a 1.5 arcsecond contribution is allowed for seeing (shear layer and cavity effects combined). Reduced image quality is allowed throughout the field of view, and for purposeful tilt of the secondary mirror, as indicated by the chosen design.

### Telescope Wavefront Error Budget - 2 m Aperture

The SOFIA telescope wavefront error (WFE) budget is based on the image quality requirements previously stated. These specifications are for a static telescope with no space chopping, vibration, pointing jitter, or effects of atmospheric seeing. The effects on image quality from dynamic factors, are identified in the system-level image quality budget. The first error budget shown here is for a 2 m, central aperture operating at the Nasmyth focus. The budget (which follows) for the 3 m aperture can be seen to have allocations for focus and alignment that are larger due to the primary mirror operating at  $f/1$ . Budgeting for all of the contributors of WFE has been carried out to achieve a diffraction limited telescope by Marechal's Criterion. The contributing wavefront errors are root-sum-squared together to arrive at a total rms WFE for the whole telescope. Then by the Marechal Criterion, the diffraction limited wavelength is 14 times the total rms WFE.

### TELESCOPE WAVEFRONT ERROR BUDGET - 2 M APERTURE



#### Telescope Wavefront Error Budget - 2 m Aperture (cont'd)

In many instances, the budget allocations are derived in the System Engineering Report (SER) "Preliminary Error Budget and Tolerances" contained in SOFIA Study Office files. In the SER, tolerances and wavefront errors are provided for a choice of system f/ratios, f/13.5 or f/17. Where the f/ratio matters, the tighter tolerance is adopted. The allocation for optical metrology is based on an estimate of what is presently possible. Where analysis has provided additional information other allocations have been made, as in the case of the primary mirror mount. An allocation for a pressure window is included. If a science instrument is pressure sealed, then this allocation may be deleted from the budget.

NASTRAN analyses of the entire baseline mirror and mount provided surface deflections that were analyzed with Program FRINGE. The results indicate that rms wavefront errors of 0.1 wave are reasonable for the lower spatial frequencies preserved by FRINGE. An additional allocation of 0.05 wave has been added to recognize the effects of higher spatial frequencies. This result is adopted for both apertures.

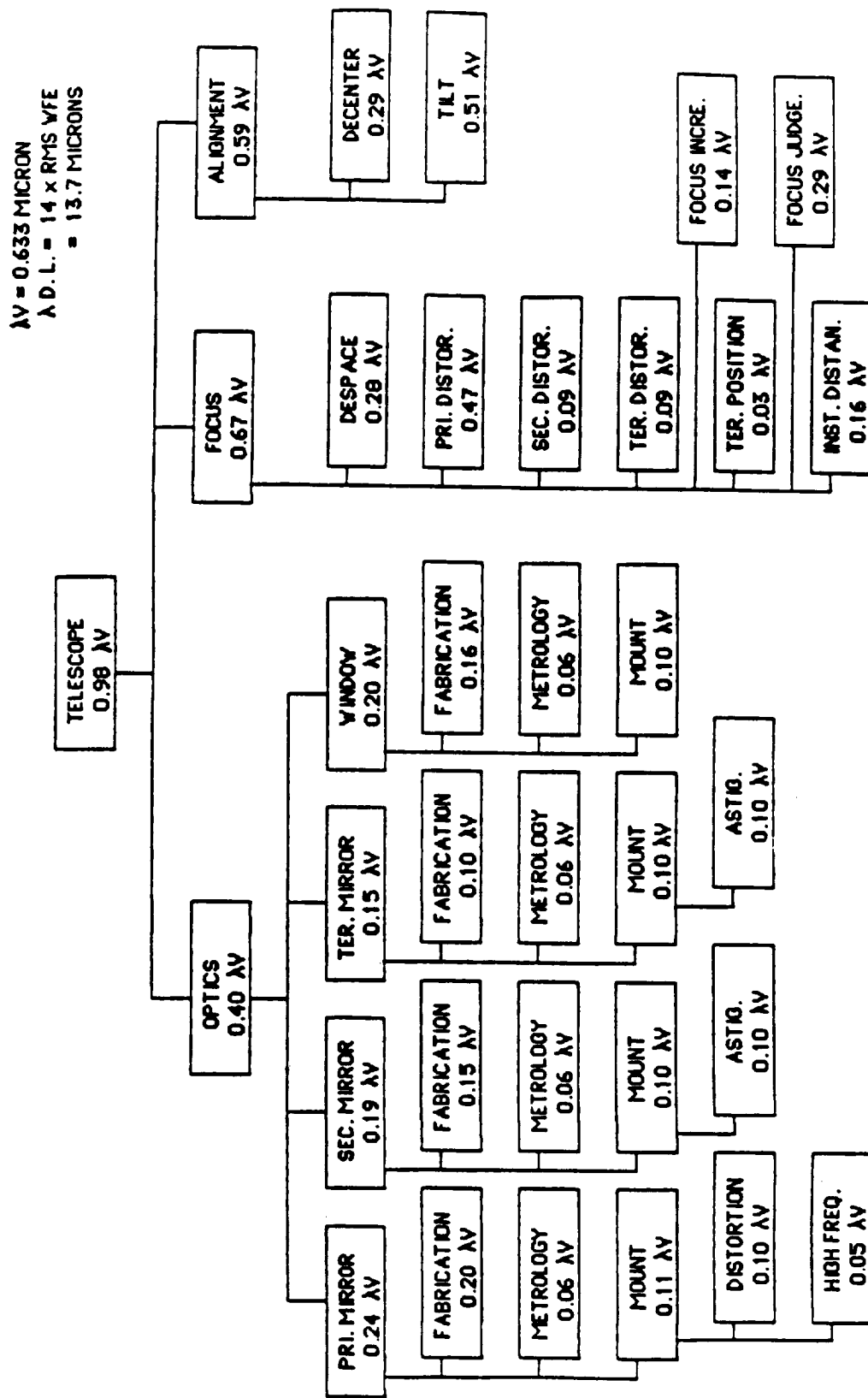
In both budgets, the primary mirror has been given the largest allocation as a consequence of the difficulty of fabrication and mounting, but not by a large difference. As indicated above, the mount allocation includes both low spatial frequency errors (such as astigmatism) and high spatial frequency errors. The secondary and tertiary mirror mounts are budgeted to allow for one low frequency term each, astigmatism. Focus includes the usual allowance for primary to secondary spacing error. It is derived from a tolerance of 5 microns. The other focus terms place limits on changes in focus from the other optical elements due to changes in elevation or in temperature during the time span of an observation. The allowances for alignment are derived from tolerances of 50 microns of secondary mirror decenter and 50 arcseconds of tilt.

#### Telescope Wavefront Error Budget - 3 m Aperture

The diffraction limited wavelength arising from the Marechal Criterion for the 3 m aperture is 13.7 microns. This diffraction limited wavelength may be compared to the performance using the central 2 m aperture by noting the larger wavefront error allocations in focus and alignment at 3 m. It has been assumed that the mechanical performance of the structure and focusing/tilt mechanism are the same for either aperture. Therefore, with the primary operating at f/1, the wavefront errors resulting from despace, decenter, and tilt tolerances are larger, as is indicated in a following subsection entitled "Effects of the f/1 Primary Mirror."

As one might expect, the primary mirror mount and other mounts are the same for both apertures, so that the wavefront allocations for the two apertures are the same.

### TELESCOPE WAVEFRONT ERROR BUDGET - 3 M APERTURE



## Optical Tolerances

The accompanying table presents tolerances for the SOFIA telescope based on the optical requirements of producing a 1 arcsecond diameter point source image when the telescope is stopped down to a 2 meter aperture, and producing better than a 3 arcsecond diameter point source image when the full aperture is used. (In actual operation the image would be further degraded by "seeing", and will be of reduced quality at the edge of the field and when the secondary mirror is tilted beyond the stated tolerance, for "chopping".)

A 2m aperture at a wavelength .5 micron produces an image with an Airy (diffraction) diameter of .126 arcseconds on the sky. Thus the telescope is not required to be diffraction limited at the wavelength where its quality is specified. This unfortunately means that the standard root-mean-square wavefront error analysis is not strictly true. The actual image quality will depend not only upon the r.m.s. wavefront error, but also upon the specific errors which are present. These latter are unknown, and usually unknowable, until the telescope is actually constructed. Therefore analysis was performed assuming an average effect, based on defocus and astigmatism as the optical forms of the error.

Each tolerance in the table may result from a variety of effects in the telescope. The tolerance should be applied to the combination of all effects. Among the ingredients in each will be such matters as manufacturing, alignment, thermal distortions, gravitational effects as the elevation angle is changed, aircraft and wind induced vibrations, chopping mechanism vibrations, and others.

The column labeled "absolute" must be interpreted as applying to all possible causes, but there is some relief in the other two columns. Because of the ability to focus the telescope, some errors can be compensated. In such cases as stability during the course of an observation, system vibrations are important. The column labeled "stability" presents such tolerances. Yet other errors will be compensated for by the guidance system. When a focal plane guidance system is used, only vibrational effects of high enough frequency to escape correction by the guidance system are relevant. The column labeled "jitter" presents tolerances for such effects.

When there is no tolerance in a column, those effects are to be considered part of the effects whose combined limit is given in a column to the left. The absence of an "absolute" tolerance does not mean that any error can be accepted, but only that an error does not immediately reduce the imaging ability of the telescope. Tolerances in these columns will usually result from non-optical considerations.

### SOFIA OPTICAL TOLERANCES

Parameter	Value	Absolute	Stability	Jitter
Primary mirror focal length	3000			
Primary mirror central sag	188		.008 mm .0005 mm	
Primary mirror surface error		.000127 mm		
Central area surface error		.000063 mm		
Primary mirror distortion		.00075 mm		
Primary mirror tilt vector				.05 arcsec
Secondary mirror focal length	320		.002 mm	
Secondary mirror central sag	17		.0001 mm	
Secondary mirror surface error		.000033 mm		
Secondary mirror distortion		.00015 mm		
Secondary versus primary decenter		.05 mm		.001 mm
Secondary mirror tilt vector		60 arcsec		.5 arcsec
Distance from primary to secondary	2700		.005 mm	
Tertiary mirror central sag	0		.0001 mm	
Tertiary mirror surface error		.000033 mm		
Tertiary mirror distortion		.00015 mm		
Distance from primary to tertiary	920		.2 mm	.01 mm
Tertiary mirror tilt vector	45 degree			.5 arcsec
Distance from axis to instrument			.5 mm	
Instrument misposition vector				.02 mm

### Effects of the f/1 Primary Mirror

In order for the 3-m telescope to fit within the aircraft cavity its length will also be limited to about 3 meters. This will result in a primary mirror which is approximately f/1, that is, its focal length is the same as its diameter.

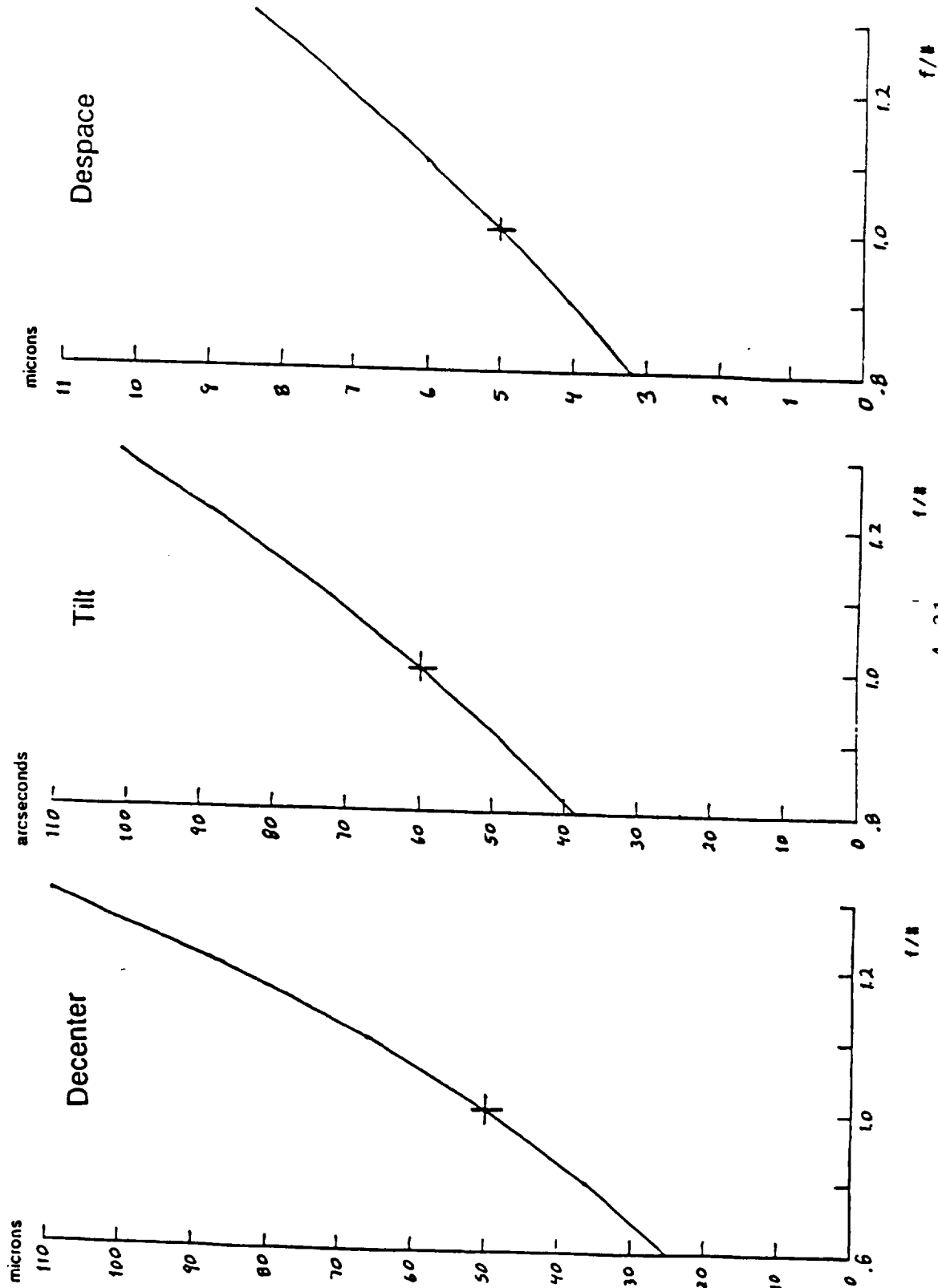
There are two undesirable side-effects of such a "fast" primary. They are a reduced quality field of view, and tight tolerances on the positioning of the secondary mirror with respect to the primary.

If the third-order optical design is either paraboloidal-primary or Ritchey-Chretien, and the telescope is designed for the required image quality and unvignetted field of view, the image diameter at the edge of the field will be about 25 percent larger than at the center, at visible wavelengths. At infrared wavelengths beyond about 10 microns the full unvignetted field will be of comparable quality to the center of the field.

The accompanying three graphs show the mechanical tolerances as a function of the primary mirror focal ratio. "Decenter" means a lateral shift between the axis of the primary mirror and the center of the secondary. "Tilt" means a deviation from parallel of the surfaces of the two mirrors as determined by planes tangent to the mirrors at their centers of figure. "Despace" means change in the distance between the mirrors.

As can be seen, these are quite tight, especially the "despace". The decenter tolerance must be met and maintained by the telescope structure under all circumstances. The tilt tolerance is the limit to which the line of sight can be changed by tilting the secondary. (Note that the angular change in line-of-sight is one fifth of the secondary mirror tilt for SOFIA.) The despace tolerance is the allowable drift between focusing operations, plus any vibrational motion.

## SECONDARY MIRROR MECHANICAL TOLERANCES VS PRIMARY MIRROR FOCAL RATIO



### Candidate Primary Mirror Technology

The weight of the SOFIA telescope is a significant driver of the overall system weight and therefore of the performance of the flight system observation time at altitude. A 1500 lb. boundary for the weight of the primary mirror has been identified as the approximate value at which penalties in observation time begin to be incurred.

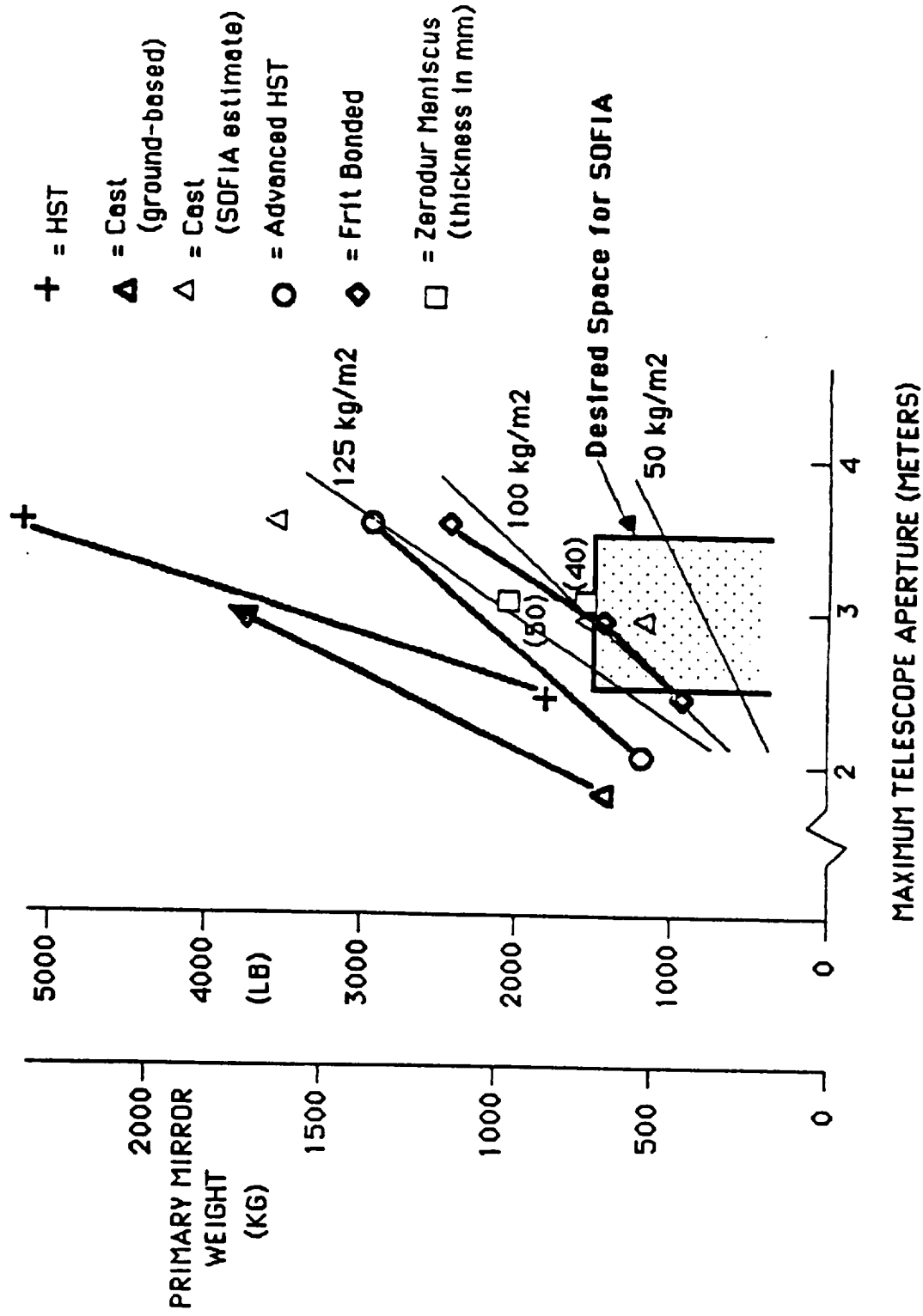
The lower boundary of maximum telescope aperture has been set for scientific reasons. At the beginning of the Boeing aircraft modification studies, an upper bound aperture of 3.5 m was set for investigation of the feasibility of aircraft modification. The studies have since shown that a number closer to 3 m is likely to be the maximum aperture that can be accommodated.

Several primary mirror technologies are readily identifiable as candidates for the telescope on the basis of size. However, some are easily eliminated because at the required size they are far heavier than desired. One of the best known is that of the Hubble Space Telescope (HST). It is fusion-bonded ULE. Though an "Advanced-HST" (A-HST) technique has been worked out to reduce the weight of the fusion-bonded approach, it is still much heavier than required to get into the desired space of size and weight (see following graph). The next 2 graphs are shown as linear, when in fact they are slightly nonlinear. However, only insignificant errors are involved.

The cast, borosilicate design developed at the Steward Observatory intended for large ground-based telescopes has an areal density of about  $250 \text{ kg/m}^2$ . As depicted, such an areal density cannot intersect the desired space. Estimates have been prepared by Steward Observatory for lighter-weight castings. An early 3.5 m estimate was 1600 kg. This density is  $166 \text{ kg/m}^2$ . Estimates of much lower densities prepared for MAN are shown inside the desired space.

Estimates of weights for thin, solid-meniscus Zerodur mirrors, have been prepared by Zeiss. A thickness of 50 mm corresponds to an areal density of  $125 \text{ kg/m}^2$  (not subtracting the mass removed for the center hole). For constant thickness, a meniscus of any size falls on the line representing that areal density. A mirror of this density can get into the desired space between 2.6 m and 2.7 m, at the 1500 lb. weight boundary. If the thickness is reduced to 40 mm, the areal density is  $100 \text{ kg/m}^2$ , allowing up to 3 m before hitting the weight boundary. Estimates of the weight of frit-bonded mirrors were prepared by Eastman Kodak and Corning for sizes of 2.4 m, 2.9 m, and 3.5 m. The estimate for 2.9 m falls right on the 1500 lb. weight boundary. Still lighter weights can be achieved by going to the composite technologies. The leading candidate is graphite epoxy. Areal densities well below  $50 \text{ kg/m}^2$  can be achieved. The examples of reflectors made and tested to date cannot be expected to perform to the image quality requirements that are expected for SOFIA, particularly over the temperature range. Additional concerns include long-term stability, a suitable surface for polishing, and satisfactory smoothness.

## CANDIDATE PRIMARY MIRROR TECHNOLOGY



### Primary Mirror Size/Weight Trade Space

This graph is an enlargement of the desired size and weight trade space. A lower limit on size (diameter) has been set that is firm for scientific reasons. As mentioned previously, an upper limit of about 3 m has been identified from aircraft studies. The upper weight boundary is identified as beginning at 1500 lb. where, based on a study of system weight and aircraft performance, a penalty in flight observation time becomes important. While there is no lower bound shown, in practice for a given technology it will be governed by lack of mirror stiffness. This study did not explore a lower limit.

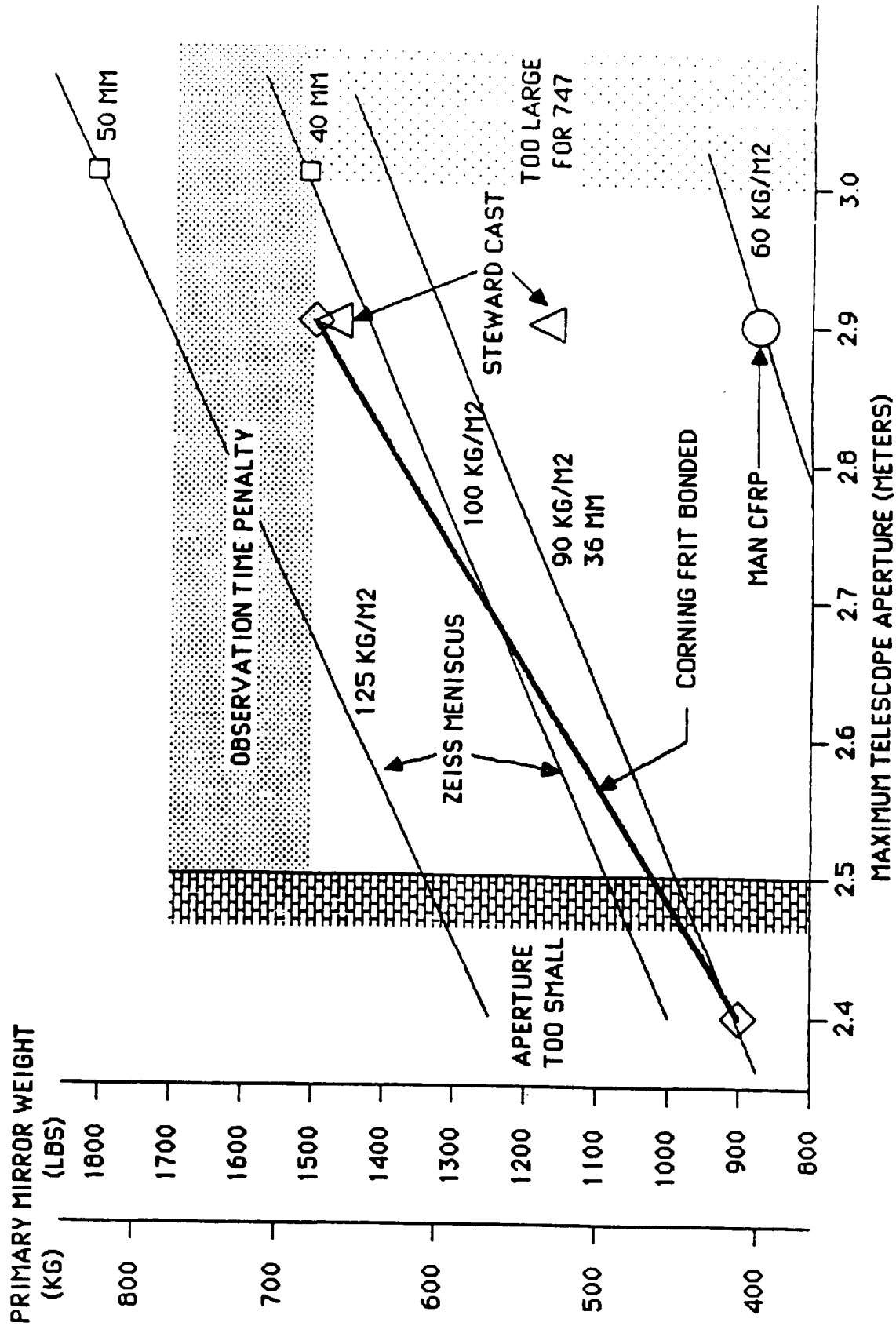
The prominent heavy line connects the two size and weight estimates prepared by Kodak for MAN, for the Corning frit-bonded mirror technology. The two end points correspond to areal densities of about 90 and 110 kg/m<sup>2</sup>, respectively. This technology is well within the desired space.

Four lines of constant areal density are shown from 125 down to 60 kg/m<sup>2</sup>. The top two of the lines are representative of solid, thin menisci mirrors made of Schott Zerodur at constant thicknesses of 40 mm and 50 mm. Studies by Zeiss of the meniscus indicate that this technology is a viable candidate.

Also shown are two estimates prepared by the Steward Mirror Laboratory for spin-cast borosilicate blanks. The estimates were prepared in collaboration with the MAN study.

Near the lowest areal density shown, is an estimate provided by MAN for the Carbon Fiber Reinforced Plastic (CFRP) technology. It has great promise for reducing the weight of the telescope and consequently the whole system. Much needs to be done to determine the expected optical performance of a large mirror made of this material.

## SOFIA PRIMARY MIRROR SIZE/WEIGHT TRADEOFF



### Lightweight Primary Mirror Blank Technology for SOFIA

Since one of the key drivers in the weight estimate for the system is the weight of the primary mirror, it is appropriate to examine examples of lightweight mirror technology that are available. The table is arranged to show what has been accomplished in lightweight mirrors. Perhaps best known is the Hubble Space Telescope (HST) mirror, which has been finished to  $\lambda/70$  rms. Though it has an  $f/ratio$  not too different from conventional, ground-based telescopes, it is much lighter and probably represents the state-of-the-art in optical quality for a lightweight, astronomical telescope. It provides a well-documented benchmark.

Recently, efforts at the Steward Mirror Laboratory have produced spin-cast mirror blanks of borosilicate glass in a lightweight, honeycomb-core, sandwich construction. The VATT mirror is significantly more dense than the HST and much more than what is desired for SOFIA (about 90 kg/m<sup>2</sup> at 3 m dia.), but it will be an  $f/1$  mirror and will ultimately demonstrate the polishing technology at the  $f/ratio$  needed. The borosilicate glasses that are used in the spin-cast furnace do not have the low expansion coefficients of the higher-cost, higher-temperature Ultra Low Expansion (ULE) fused silica, or the glassy-ceramic Zerodur. Careful evaluation of the thermal performance of a borosilicate mirror for SOFIA will be required. The 3.5 m mirror for the ARC Consortium telescope will take the spin-cast technology even beyond the SOFIA size, but at a higher areal density.

Steward Observatory in collaboration with MAN has estimated that a spin-cast mirror for SOFIA can be made significantly lower in density than the current VATT or ARC blanks. This would be accomplished by casting thinner face sheets and ribs.

The Zeiss proposal for their feasibility study of SOFIA contained in it a solid, 77 mm thick meniscus of Zerodur. Further study by Zeiss of the properties of the blank suggests that a still thinner meniscus of 50 mm or even 40 mm is feasible. The stiffness of a solid meniscus that thin will be a significant design problem for suitable mounting both in polishing and for flight.

The Kodak/Corning, frit-bonded fabrication technology produces a low-density, fused-silica blank in a sandwich form. This form is desirable for its inherent stiffness. The low expansion of fused silica provides important advantages in thermal performance. The largest size mirror designed using this technology is reported to be 1.5 m in diameter at an areal density of 32 kg/m<sup>2</sup>.

Though efforts are being made to develop carbon Fiber Reinforced Plastic (CFRP) mirror blanks for SOFIA by the German companies MAN-Technologie and Dornier Systems, they are difficult to evaluate without published performance of the several different, small composite mirrors that have been tested over a temperature range.

## LIGHTWEIGHT PRIMARY MIRROR BLANK TECHNOLOGY FOR SOFIA

<u>AREAL DENSITY</u> (KGM2)	<u>APPLICA.</u>	<u>TYPE</u>	<u>DIA.</u> (M)	<u>MATERIAL</u>	<u>F/RATIO</u>
<u>ACCOMPLISHED:</u>					
184	HST	FUSED	2.4	ULE	2.3
252	VATT <sup>1</sup>	SPIN-CAST	1.8	OHARA E6	1.0
23	DEVEL.	FRIT	0.5	FUSED SILICA	2.0
<u>SCHEDULED:</u>					
197	ARC <sup>2</sup>	SPIN-CAST	3.5	OHARA E6	1.75
32	DEVEL.	FRIT	1.5	ULE	?
<u>STUDIED:</u>					
165	SOFIA <sup>3</sup>	SPIN-CAST	3.5	OHARA E6	1.0
127	SOFIA <sup>4</sup>	MENISCUS	2.8	ZERODUR	1.0
110	SOFIA <sup>5</sup>	FRIT	2.9	ULE	1.0
103	SOFIA <sup>6</sup>	CAST	2.9	OHARA E6	1.0
60	SOFIA <sup>7</sup>	COMPOSITE	2.9	CFRP	1.0

<sup>1</sup> VATT = VATICAN ADVANCED TECHNOLOGY TELESCOPE, PRESENTLY FUNDED

<sup>2</sup> ARC = ASTROPHYSICAL RESEARCH CORP. (U. CHICAGO, PRINCETON U., U. WASHINGTON, U. NEW MEXICO).

<sup>3</sup> TO BE CAST IN SPRING '88, LOCATION - APACHE POINT, NEW MEXICO.

<sup>4</sup> ESTIMATE FROM STEWARD OBSERVATORY LETTER OF 7/5/85

<sup>5</sup> ZEISS STUDY MIDTERM ESTIMATE, THICKNESS = 50 MM

<sup>6</sup> ESTIMATE FROM CORNING

<sup>7</sup> STEWARD OBSERVATORY "REASONABLE GOAL" ESTIMATE, MAN STUDY FINAL REPORT

MAN STUDY FINAL REPORT

### Finishing Technology for Low F/Ratio Primary Mirrors

Historically, lapping and polishing of telescope primary mirrors has been accomplished using stiff, full-diameter tools. At about  $f/2$ , even a smaller, sub-diameter lap has difficulty conforming to an aspheric mirror surface, which has different curvatures in the radial and tangential directions. Flexible laps that conform to the surface have been used with some success as evidenced by the  $f/0.8$  example.

The table is arranged for increasing  $f$ /ratio. Clearly, at  $f$ /ratios below the transition to full diameter rigid laps, there are several different approaches to polishing. The  $f/0.8$  mirror is important in that it indicates that  $f/1$  is not below some absolute lower limit.

In support of its work with  $f/1$  mirrors, Steward Observatory is pursuing a stressed-lap concept. In this concept, computer-controlled actuators around the sub-diameter lap actively control the shape of a flexible lap so that it will conform to the highly aspheric surface. The concept has been demonstrated in the laboratory with a sub-scale, spring-loaded analog of the active lap. Work is underway on the polishing machine for the  $f/1$  VATT mirror. Successful polishing of this mirror will demonstrate another solution to the low  $f$ /ratio mirror finishing problem.

Small-diameter tools under computer control have successfully polished a number of mirrors, hence the name Computer Controlled Polishing (CCP) used by Perkin-Elmer. The HST mirror was polished using this concept. Other companies such as Itek and Tinsley (just to name two), have computer controlled polishing machines. The tools, unless flexible, must be quite small to conform to the shape of an  $f/1$  surface. However, in practice small tools must be used with great care to prevent the inadvertent generation of ripple in the surface that can only be effectively reduced by a larger lap. There is no reason in principle that a computer-controlled, small lap machine could not be employed successfully to polish an  $f/1$  mirror.

A concept invented by Zeiss is called the membrane lap. This concept calls for a flexible membrane to be stretched over the mirror. It is held in tension around its periphery to prevent wrinkles. Pads with variable pressure press the membrane into contact with the surface. The membrane is drawn across the mirror and under the pads to effect the polishing action. The capability of this concept will require further investigation.

The ARC primary mirror for the Apache Point telescope is a large mirror of intermediate  $f$ /ratio. It will be polished by sub-diameter laps, and may be near the smallest  $f$ /ratio that can be polished without resorting to very small or flexible laps.

### FINISHING TECHNOLOGY FOR LOW F/RATIO PRIMARY MIRRORS

<u>POLISHING METHOD</u>	<u>F/RATIO</u>	<u>DIA. (M)</u>	<u>TYPE</u>	<u>MATERIAL</u>	<u>STATUS</u>
FULL LAP	0.8	1.2	FUSED	ULE	COMPLETE <sup>1</sup>
STRESSED LAP	1.0	1.8	SPIN-CAST	OHARA E6	FUNDED
MEMBRANE LAP	1.0	2.8	MENISCUS	ZERODUR	DEVELOPMENTAL
SUB-DIAMETER LAP <sup>2</sup>	1.75	3.5	SPIN-CAST	BOROSIL	PLANNED <sup>3</sup>
SMALL LAP <sup>4</sup>	2.3	2.4	FUSED	ULE	COMPLETE
FULL LAP <sup>5</sup>	2.3	2.4	FUSED	ULE	COMPLETE

<sup>1</sup> DEPT. OF DEFENSE FUNDED DEMO (NO EXPORT TECHNOLOGY RESTRICTION)

<sup>2</sup> POLISHING BY NORM COLE, TUCSON

<sup>3</sup> WILL BE THE FIRST 3.5 M, SPIN-CAST PRIMARY

<sup>4</sup> COMPUTER CONTROLLED POLISHER; HST FLIGHT UNIT - PERKIN ELMER CORP.

<sup>5</sup> FULL DIAMETER LAP; HST ALTERNATE - EASTMAN KODAK

### Concerns and Risks

In the fabrication of the required large, lightweight, primary mirror blank, a strong candidate is the Kodak/Corning frit-bonded technology. At this time the largest mirror under construction of this type is 1.2 m in diameter. The combination of substantial size extrapolation, coupled with the  $f/1$  requirement suggests some risk until additional engineering and fabrication has been carried out to larger sizes. Though the thin meniscus is an alternative technology, here too, the extrapolation to the desired size at the thickness of 40 to 50 mm is a large jump from what has been accomplished to date.

The finishing technology for a large, lightweight,  $f/1$  primary mirror is limited to the work done at Kodak on the 1.2 m diameter  $f/0.8$  mirror and the stressed lap development at Steward Observatory. Neither of these techniques has been applied to a mirror with the low areal density needed for SOFIA. It is important that the first example was successful and that the second is under active development. This experience reduces the risk that all new techniques will have to be developed solely for the SOFIA program. It is possible to reduce the risk in polishing by relaxing either the image quality requirements or by increasing somewhat the  $f$ /ratio of the mirror at some expense in aperture.

It is not yet known what the magnitude of high spatial frequency surface errors in the primary mirror will mean for the imaging performance of the telescope. Of particular concern is the visible performance required for the scientific objectives and for the fine guidance sensor operating at the telescope focus. Further analysis will quantify this aspect of primary mirror quality.

The strength of a lightweight glass mirror is a concern in that the desire to reduce weight tends to raise stress levels in the material. The main risk is a broken primary mirror from handling or high load conditions associated with flight, such as a hard landing. Risk can be reduced by increasing the amount of material in the mirror with an attendant weight or size penalty. There may be a limit on the maximum web thickness that can be used in the frit-bonded core, however, so that the strength/weight tradeoff is not clear. It is clear that the meniscus can be increased in thickness quite easily if desired.

The mechanical tolerances associated with an  $f/1$  primary mirror will lead to some stringent error budgeting for the mechanical and thermal design of the telescope. Focus is the most obvious example, with an allowance of only 5 microns change in mirror spacing during the time an observation is made.

### CONCERNS AND RISKS

- FABRICATION OF THE LARGE, LIGHTWEIGHT PRIMARY MIRROR BLANK
  - RISK: COST, SCHEDULE GROWTH
  - RISK REDUCTION: EARLY DESIGN STUDIES, TECHNOLOGY DEVELOPMENT, CONSIDER USING ALTERNATIVE TECHNOLOGY
- FINISHING OF THE F/1 PRIMARY MIRROR
  - RISK: COST, SCHEDULE GROWTH
  - RISK REDUCTION: TECHNOLOGY DEVELOPMENT, REDUCE IMAGING REQUIREMENTS
- STRENGTH OF PRIMARY MIRROR
  - RISK: MIRROR FRACTURE
  - RISK REDUCTION: INCREASE WEIGHT/REDUCE APERTURE - MARGIN EXISTS BELOW 3M TO MEET 680 KG (1500 LB) OBJECTIVE
- HIGH SPATIAL FREQUENCY, PRIMARY MIRROR SURFACE ERRORS
  - RISK: COST OF ADDITIONAL ANALYSIS AND DESIGN
  - RISK REDUCTION: EARLY DESIGN STUDIES, ADDITIONAL MOUNT CAPABILITY
- MECHANICAL TOLERANCES ASSOCIATED WITH THE F/1 PRIMARY MIRROR
  - RISK: FOCUS, IMAGE QUALITY VARY WITH TEMPERATURE, ELEVATION
  - RISK REDUCTION: DESIGN STUDIES, REDUCE APERTURE AND MIRROR F/RATIO
- LOW INERTIA SECONDARY MIRROR FOR CHOPPER
  - RISK: LESS DYNAMIC PERFORMANCE OF THE CHOPPER
  - RISK REDUCTION: TECHNOLOGY DEVELOPMENT

## Optics Summary

The SOFIA telescope will be a Cassegrain/Nasmyth. It will have a primary mirror of 2.5 to 3 meters diameter and focal ratio near  $f/1$ . The system focal ratio will be adjustable from  $f/11$  to  $f/18$  by interchange of secondary mirrors. Two secondary mirrors will be supplied designed for  $f/13.5$  and  $f/17$ .

The fast and highly curved  $f/1$  primary is called for to fit the telescope within the aircraft. While this concept has difficulties, it appears they are not insurmountable. Thus a telescope design is feasible which has the maximum aperture geometrically allowed.

The primary mirror should probably have a paraboloidal figure. Either this, or a slightly hyperboloidal primary appropriate to a Ritchey-Chretien design, provides the specified image quality over the entire unvignetted field for wavelengths greater than about 17 microns, and for even shorter wavelengths if field-flattening optics or curved detectors are used.

Wavefront, focus, and image jitter error budgets have been developed from which mechanical tolerances have been developed. Some of these tolerances are quite tight given the aircraft environment. A selection of these have been studied in more detail, results being presented in other sections of this report. It does appear that all of the tolerances can be met, provided proper design decisions are made.

A number of technologies have been identified that can be employed in the fabrication of the large, fast, lightweight primary mirror blank, and in the finishing of the mirror. Nevertheless, fabrication and finishing remain extremely important areas worthy of study and technology development.

### **SELECTED CONCEPTS AND ALTERNATIVES**

- CASSEGRAIN TELESCOPE WITH TERTIARY FLAT FOR NASMYTH FOCUS
- CLASSICAL CASSEGRAIN OPTICAL DESIGN
  - ALTERNATIVE: RITCHY-CHRETIEN
- FRIT-BONDED ULE PRIMARY MIRROR
  - ALTERNATIVES: THIN MENISCUS OF ZERODUR, CAST BOROSILICATE
- TELESCOPE METERING STRUCTURE
  - ALTERNATIVE: MORE FREQUENT REFOCUS AND ALIGNMENT
- LOW-INERTIA SECONDARY FOR CHOPPING
  - ALTERNATIVE: HIGHER INERTIA, REDUCED CHOPPING PERFORMANCE

## Secondary Mirror Chopper Subsystem

### Summary of Requirements

The chart shows the top-level performance and configuration requirements for the SOFIA secondary mirror assembly. The chopper mechanism must provide mirror throw amplitudes from  $\sim 10$  arcsec to 40 arcmin (2 arcsec to 8 arcmin, object space), or up to  $\pm 20$  arcmin from centered position. The mechanism must also be capable of offsetting the center of the chop from the mirror-centered position, with corresponding reduction of throw. Chopping must be performed about any axis with TBD resolution; for this purpose a 2-axis chopper has been baselined over a single-axis mechanism with rotation. (This technology has been demonstrated and provides more efficient operation.) The "transition time" (rise time) for square-wave chopping has been specified for the 5 and 20 arcmin throws, with durations  $\leq 5$  and 7 msec, respectively. Achieving this performance is expected to provide adequate capability for the other amplitudes, for which times are not specified. The driving torque requirement is then derived from the specified transition times for the given amplitudes. Required maximum chop frequencies are 10 Hz (for 20 arcmin throw) and 35 Hz (for 5 arcmin). The square wave chop end position stability is specified as  $\leq 1\%$  of the chop amplitude. Other required chop waveforms include sawtooth and "arbitrary" (e.g., sine, sine<sup>2</sup>, etc.); slow scan capability will also be necessary.

The secondary mirror itself is expected to have a  $\sim 30.5$  cm diameter, with  $\sim 2.5$  cm thickness needed for dimensional stability. To minimize thermal and mechanical distortions, low expansion glass or glass ceramic is the mirror material of choice. The chop/focus mechanism must be "hidden" behind the mirror (i.e., diameter  $\leq 30.5$  cm) and a preliminary assembly length requirement of 35.5 cm has been established. Chopping reaction forces and torques must be held to a minimum to avoid exciting the Telescope structure; if necessary, a "reactionless" design will be used. Typically, this involves use of a moving reaction mass which counteracts mirror motion to a high percentage. Since this configuration requires more power (the actuators must deflect both masses), further structural dynamic analysis is needed of the chopper/spider/heading assembly to determine if this provision is required. A final functional requirement is to provide in-flight focusing capability, both to refocus the Telescope for elevation adjustment, and to provide "focus dither" mirror motions for submillimeter science investigations. More detailed specifications for the chopper performance and configuration requirements will have to be developed in future Project phases.

### SECONDARY MIRROR CHOPPER SUBSYSTEM REQUIREMENTS SUMMARY

CHOP AMPLITUDES	.17 MIN	5	20	40 MAX	(ARCMIN, P-P; MIRROR THROW)
TRANSITION TIME	NO SPEC	≤ 5	≤ 7	NO SPEC	(mSEC, SQUARE WAVE)
FREQUENCIES	NO SPEC	1-35	1-10	NO SPEC	(Hz, INTEGER VALUES ONLY)
END POSITION STABILITY				≤ 1% OF CHOP AMPLITUDE	

#### MIRROR PROPERTIES

MATERIAL: LOW EXPANSION GLASS OR GLASS CERAMIC

DIAMETER: ~ 30.5 CM      THICKNESS: ~ 2.5 CM (DERIVED)

#### CHOPPER CONFIGURATION

DUAL AXIS ACTUATING; REACTIONLESS (IF NECESSARY)

ENVELOPE: 30.5 CM DIA X 35.5 CM LENGTH

#### FUNCTIONS

CHOP: SQUARE WAVE, SAWTOOTH, "ARBITRARY," SCAN; OFFSET CHOP

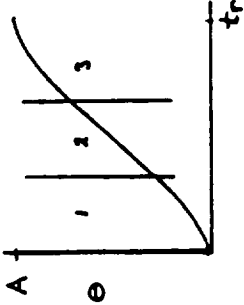
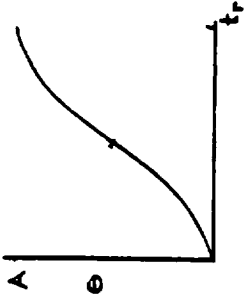
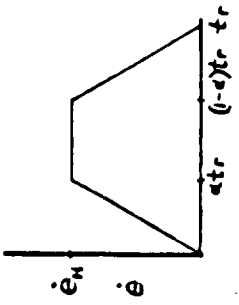
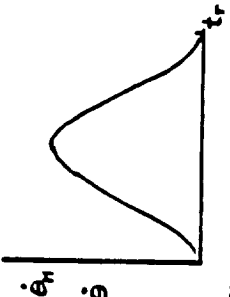
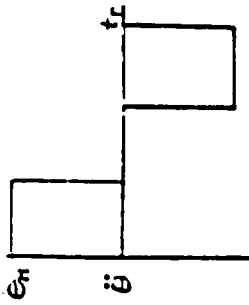
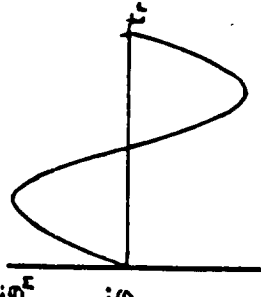
FOCUS: ADJUSTABLE, DITHER (AMPL.: .05 TO 0.5 MM; FREQUENCY: 5 TO 25 Hz)

### Chopper Transition Profiles

In order to calculate the torques required to actuate the chopper, a model of the transition profile is required. Reasonable models are based on torque pulses which can actually be produced by state-of-the-art amplifiers. Although it is impossible to produce perfect pulses, a high-bandwidth current amplifier which incorporates current feedback comes very close, assuming the motor inductance is low enough so as not to require huge voltages. A sine wave is a very reasonable approximation also, but will predict higher torques; hence it is a good, conservative approximation.

Pulse widths of 33% of the transition time will not predict as low a torque as for 50%, but theoretically will minimize the average power losses due to resistance in the armature circuit.

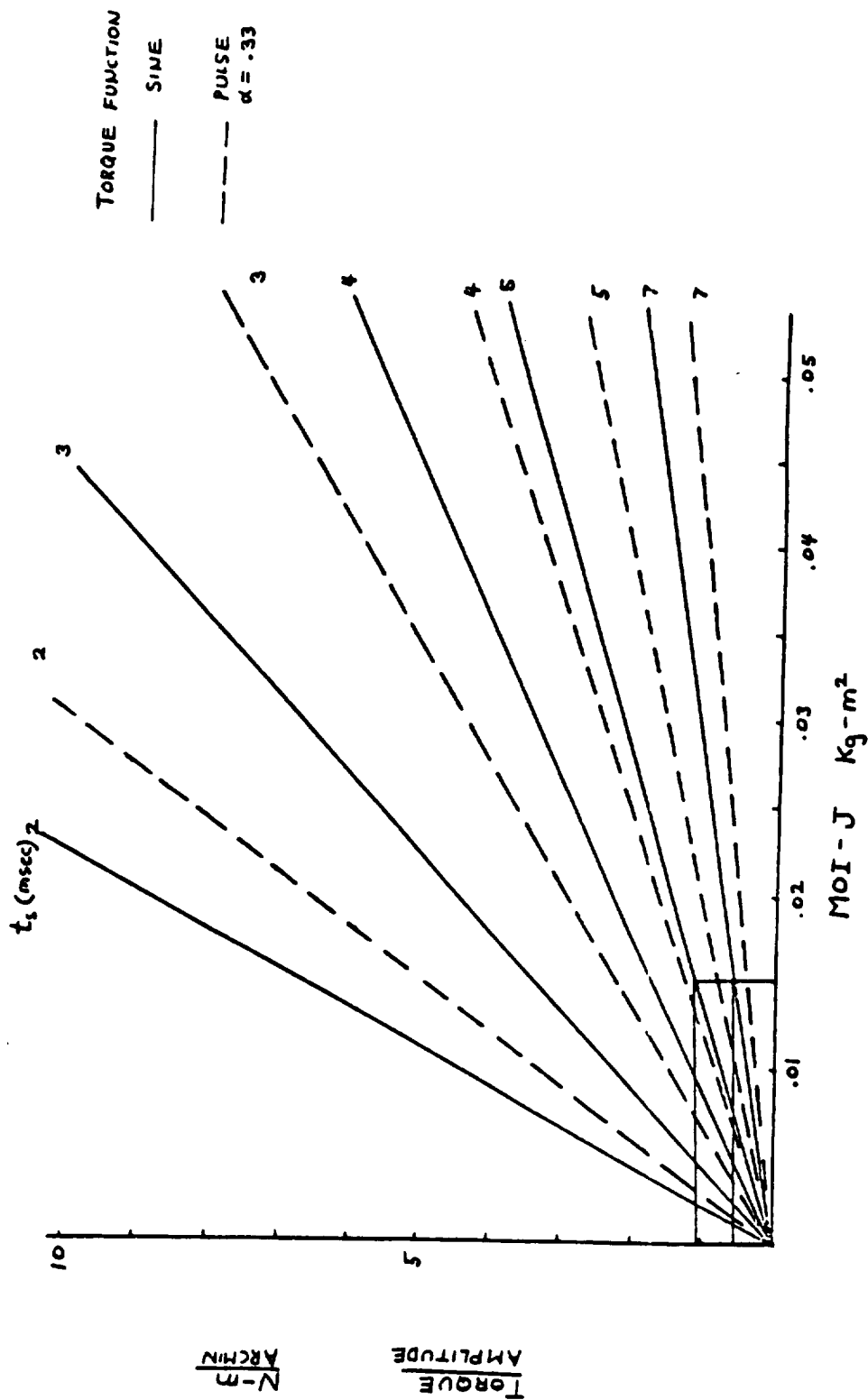
### IDEALIZED CHOPPER TRANSITION PROFILES

DERIVED FROM PULSE ACCELERATIONS	DERIVED FROM SINE ACCELERATIONS
 $\theta_1 = \frac{A}{2\alpha(1-\alpha)} \left(\frac{t}{t_r}\right)^2$ $\theta_2 = \frac{A}{1-\alpha} \left[ \frac{t}{t_r} - \frac{\alpha}{2} \right]$ $\theta_3 = A \left[ 1 - \frac{1}{2\alpha(1-\alpha)} \left(1 - \frac{t}{t_r}\right)^2 \right]$	 $\theta = \frac{At}{t_r} - \frac{A}{2\pi} \sin\left[\frac{2\pi t}{t_r}\right]$
 $\dot{\theta}_1 = \frac{A}{\alpha(1-\alpha)} \frac{t}{t_r} \left(\frac{t}{t_r}\right)$ $\dot{\theta}_2 = \frac{A}{1-\alpha} \frac{t}{t_r}$ $\dot{\theta}_3 = \frac{A}{\alpha(1-\alpha)} \frac{1}{t_r} \left(1 - \frac{t}{t_r}\right)$	 $\dot{\theta} = \frac{A}{t_r} \left[ 1 - \cos\left[\frac{2\pi t}{t_r}\right] \right]$
 $\ddot{\theta}_1 = \frac{A}{\alpha(1-\alpha)} \frac{1}{t_r^2}$ $\ddot{\theta}_2 = 0$ $\ddot{\theta}_3 = -\frac{A}{\alpha(1-\alpha)} \frac{1}{t_r^2}$	 $\ddot{\theta} = \frac{A 2\pi}{t_r^2} \sin\left[\frac{2\pi t}{t_r}\right]$

### Inertial Torque

This chart was calculated using the transition profile formulas on the previous sheet. Assuming a mirror can be made with a moment of inertia (MOI) of  $.015 \text{ Kg-m}^2$ , a torque of about  $1.1 \text{ N-m/arcmin}$  will be required to transition in 5 msec. In terms of sizing the actuators, assuming an actuation radius of .1 m and a 5 arcmin amplitude, two actuators which can produce 28 N each will be required for chopping along an actuator axis. To meet the 20 arcmin at 7 msec requirement, 57 N per actuator are required. Actuators in this range are readily available. A small additional spring torque should be considered before choosing the actuators.

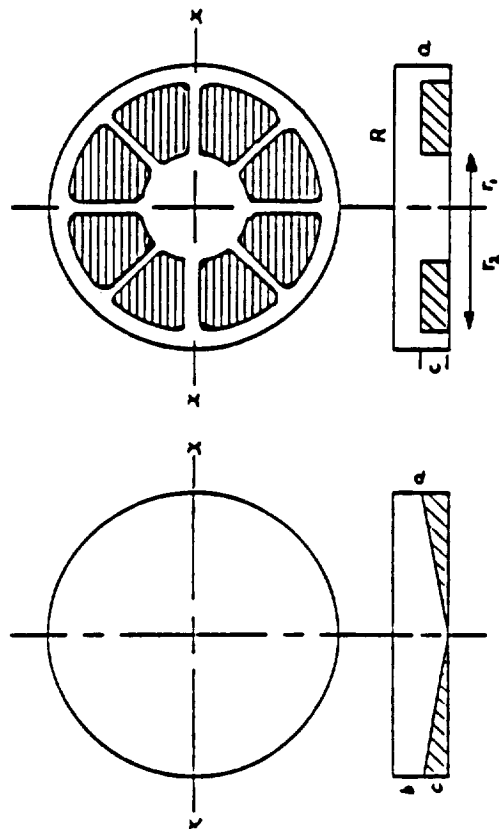
### REQUIRED INERTIAL TORQUES



### MOI Reduction

To reduce the mirror moment of inertia to as low a value as possible, it is important to machine away as much material near the perimeter of the mirror as is practicable. Based on a combination of tapering and "open-back" machining, it is possible to reduce the MOI to 60% of its original value, although a complete structural analysis should be performed to ensure that the mirror has not been weakened excessively. Starting with a 4 kg blank of fused Silica, one should be able to get a MOI of about .015 Kg-m<sup>2</sup>.

### MOI REDUCTION



$$I'_{xx}/I_{xx} = .2(4b/a + 1)$$

$$I'_{xx}/I_{xx} = 1 - c/a[(r_2/R)^4 - (r_1/R)^4]$$

#### TAPERING

$b/a$	$I'_{xx}/I_{xx}$
0	.20
1/4	.40
1/2	.60
3/4	.80
1	1.0

#### OPEN-BACK MACHINING

$I_1/R$	$I_2/R$	$c/a$	$I'_{xx}/I_{xx}$
1/8	7/8	.50	.71
1/8	7/8	.80	.53
1/2	15/16	.50	.65
1/2	15/16	.80	.43
3/8	1/8	.50	.72

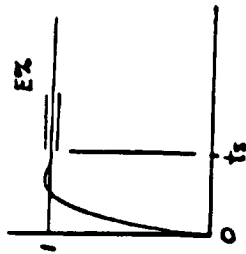
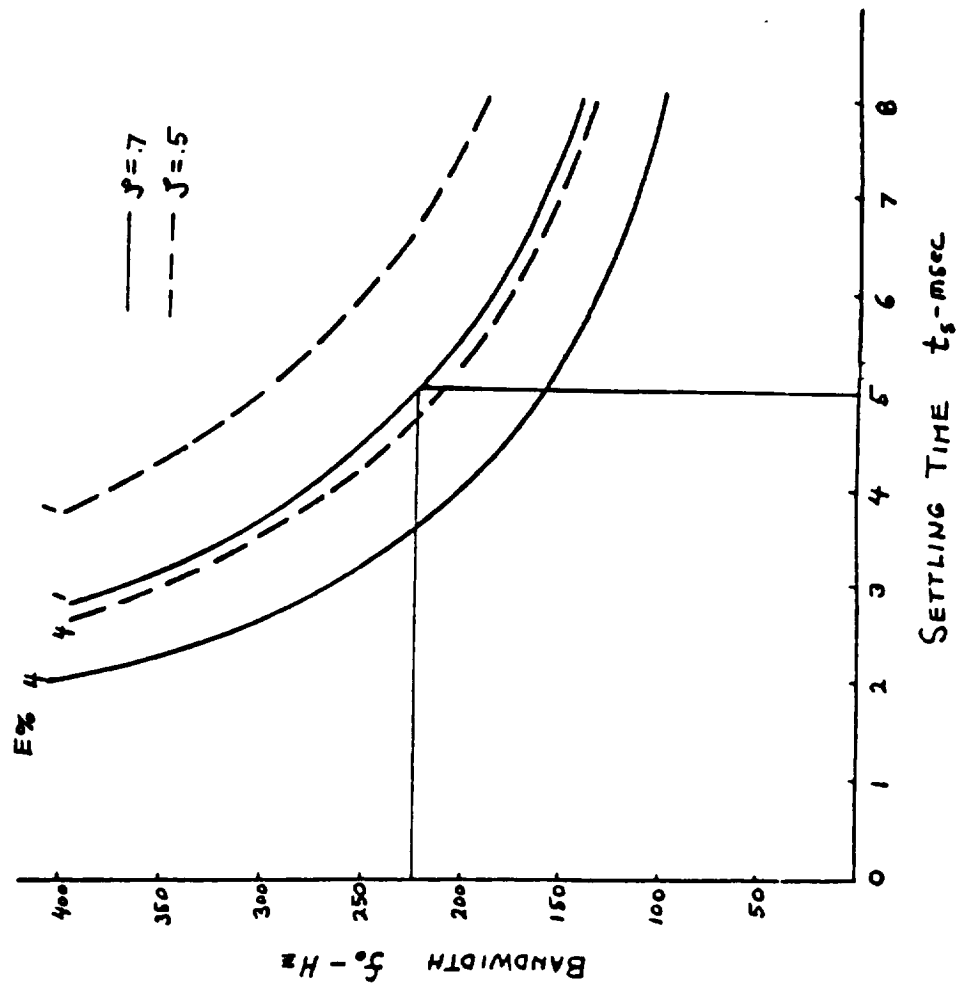
### Chopper Bandwidth Selection

The control system bandwidth must be chosen carefully to ensure that enough harmonic content is available to produce the desired chopping response. An analysis of a classical second-order step response is a suitable method of determining bandwidth.

A note about rise time and settling time: classical rise times are often quoted as the time to transition from 10-90% of the step, however overshoot may also occur after the rise time. Settling time is better suited for defining chopper performance since it is the time required for the step to reach the goal value within a defined error.

To meet SOFIA specifications of a 5 msec transition time with 1% error in the final value, a bandwidth of 225 Hz is required at a damping ratio of .7. This is consistent with bandwidths quoted for similar systems. Notice that bandwidth is a function of damping ratio. Lower damping ratios will require higher bandwidths to achieve the same settling time.

## CHOPPER BANDWIDTH SELECTION



### **Stiffness in the Chopper Mechanism**

From a survey of various existing chopper systems, one point of general agreement is that the stiffness and damping of the chopper mechanism, in particular the motor-mirror junction, must be high enough to avoid any structural resonances that will cause problems with controlling the mirror. Traditionally, any structural resonances should be 5 times higher than the desired system bandwidth.

A simple chopper dynamic model was analyzed to understand more fully the effect that unwanted resonances might have on the control system. A simple control system model was used to study the performance. Both position and velocity feedback are incorporated. However, a performance comparison is made between velocity feedback at the mirror itself, and velocity feedback directly at the motor. A simple compensator is used to achieve the desired bandwidth of 225 Hz. Parameters reflecting a possible SOFIA chopper configuration were chosen and results were generated for both a moderately stiff and compliant motor-mirror junction with .05 damping.

# CIOPPEA MODEL



## VARIABLE PARAMETERS

$$K_1 = 3.7 \times 10^6 \text{ kg-sec}^{-2}$$


### **Chopper Mechanism - Moderately Stiff System** **(Velocity Feedback at Mirror)**

A resonance near 1900 Hz is apparent from looking at the Bode diagrams -- a factor of 8.4 higher than the desired bandwidth of 225 Hz. (This value is a little higher from the one calculated for the resonant frequency of a single actuator mass, spring, damper because the system is excited in a push-pull fashion so that the eigenvalues are for two actuators as if they were tied together.)

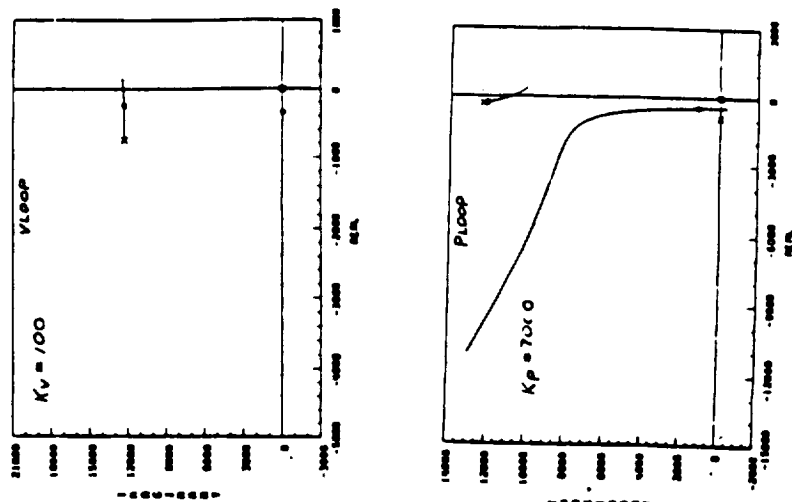
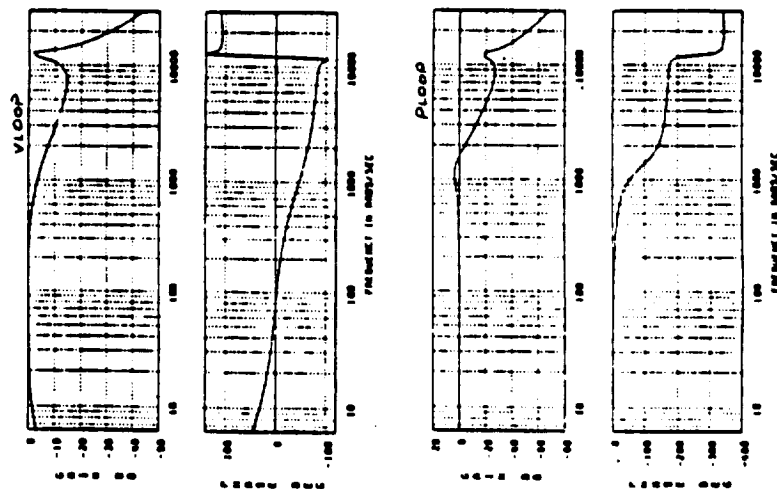
The root locus plot for the velocity loop shows how the system moves towards instability as an attempt is made to increase the velocity loop gain. It is impossible to increase the damping to a sufficiently high value and therefore the closed loop bandwidth cannot be achieved at the required damping ratio of .7. If the position gain is increased in an attempt to achieve the bandwidth (the case as shown), the damping ratio drops too low to arrive at the required settling time of 5 msec. It is not possible to get the desired performance under these circumstances.

The only other compensation option is to introduce a notch filter at the resonant frequency. This will work assuming the resonance does not move significantly. Indeed this was the solution for the Kitt Peak Observatory chopper system.

The best solution is to ensure that all system resonances are either high or well damped and to feedback the velocity at the motor instead of the mirror as shown in the following example.

### STIFFNESS IN CHOPPER MECHANISM MODERATELY STIFF SYSTEM

Velocity and Position Sensors  
Mounted on Mirror



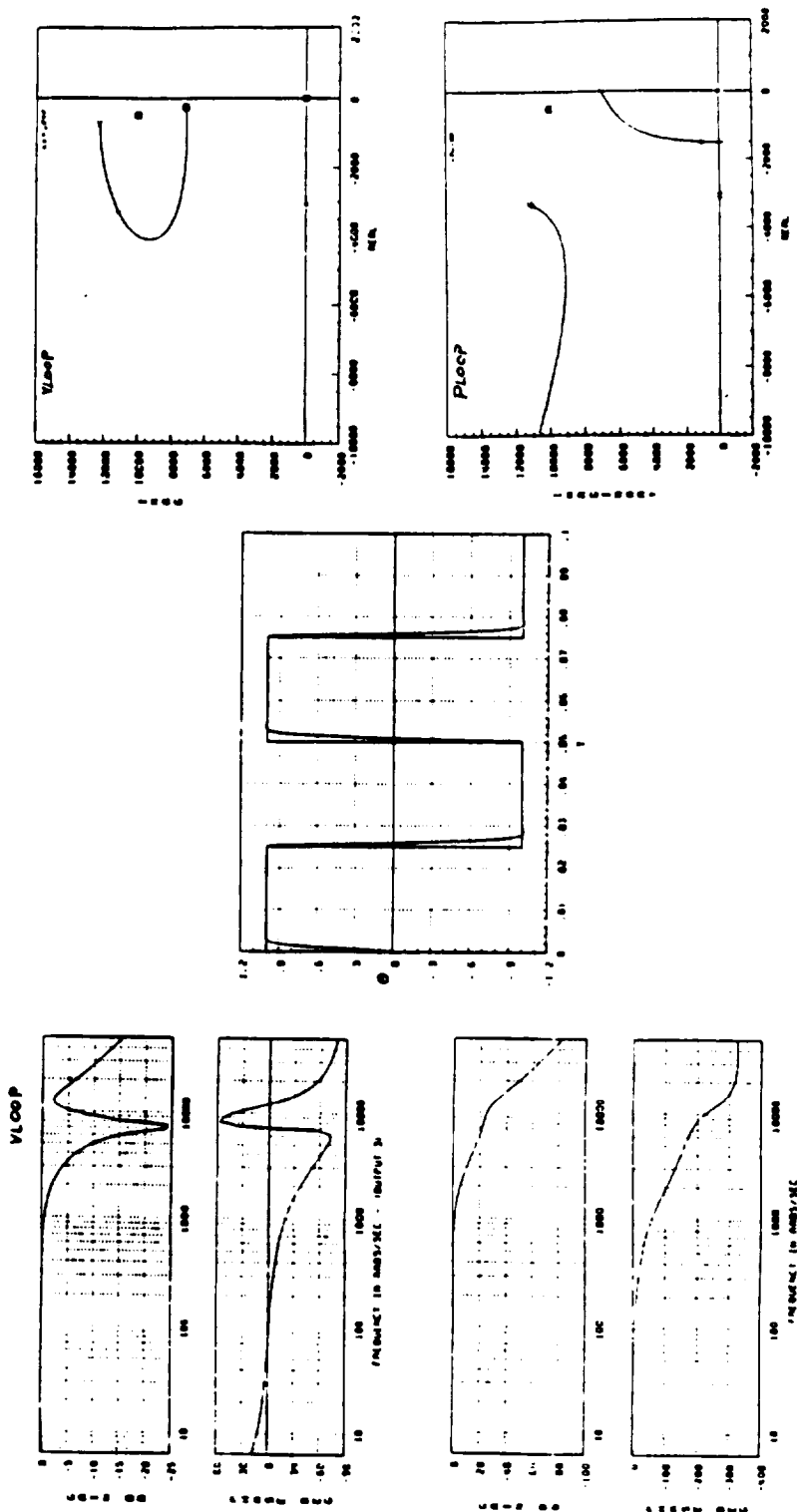
### **Chopper Mechanism - Moderately Stiff System** **(Velocity Feedback at Motor)**

A substantial increase in the performance of the system is achieved when the velocity feedback is taken from the motor rather than the mirror. Note that the position feedback is still taken from the mirror itself in order to maintain high positioning accuracy. The overall effect is similar to introducing a notch filter into the system, in that the poles are no longer drawn across the imaginary axis when the gain  $K_v$  is increased. It now becomes possible to introduce enough velocity gain into the system to achieve high bandwidth in the velocity loop. In turn, it is possible to get exceptional performance in the position loop so as to meet the required specifications.

Therefore, by simply taking the velocity feedback from the motor rather than from the mirror, the resonance at 1900 Hz presents no major problem to the control system.

### STIFFNESS IN CHOPPER MECHANISM MODERATELY STIFF SYSTEM

Velocity Sensor on Motor  
Position Sensor on Mirror



### **Chopper Mechanism - Compliant System** **(Velocity Feedback at Motor)**

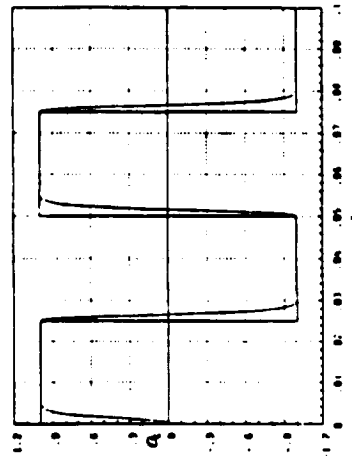
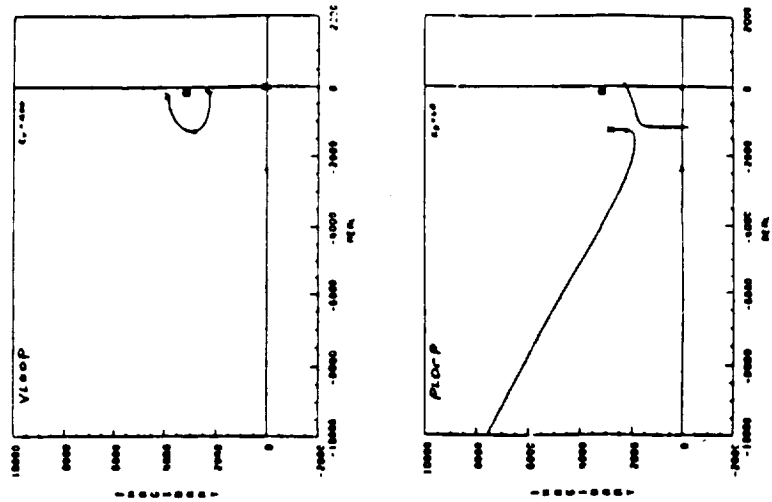
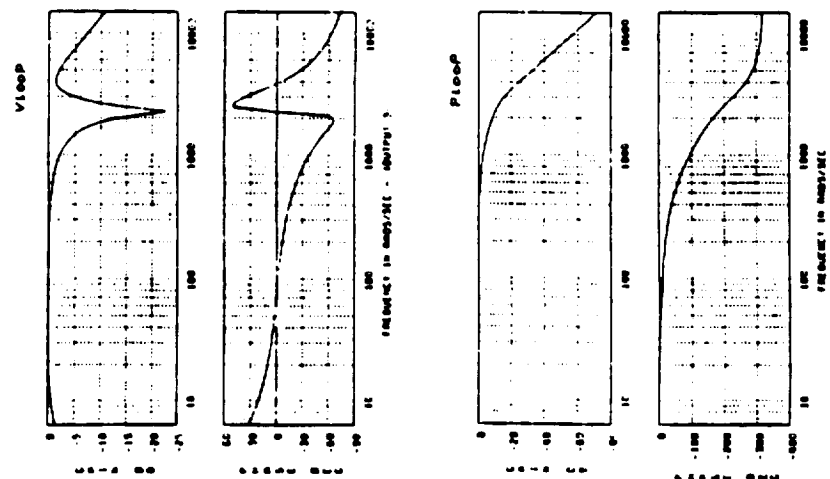
A 600 Hz resonance is close enough to the desired bandwidth of 225 Hz to cause potential problems with the control of the system. However, because of the fact that the velocity has been fed back at the motor rather than the mirror, the additional zeros make it possible to introduce enough gain into the velocity loop. An excellent response can still be obtained.

If velocity sensing had not been used, a similar response could have been simulated using a more complicated compensator which would incorporate a notch filter. In practice, however, it would be more desirable to keep the compensator electronics as simple as possible and let "nature" produce its own notch filter so as to arrive at a robust control design.

The control ideas shown here are not intended to be a final design but only to suggest the use of velocity feedback at the motor. A more practical controller would be designed to follow a transition trajectory as outlined beforehand -- maximum torques would then fall within the values previously calculated. The use of velocity and force feedforward have been demonstrated successfully by others in reducing the burden on the control system.

### STIFFNESS IN CHOPPER MECHANISM COMPLIANT SYSTEM

Velocity Sensor on Motor  
Position Sensor on Mirror



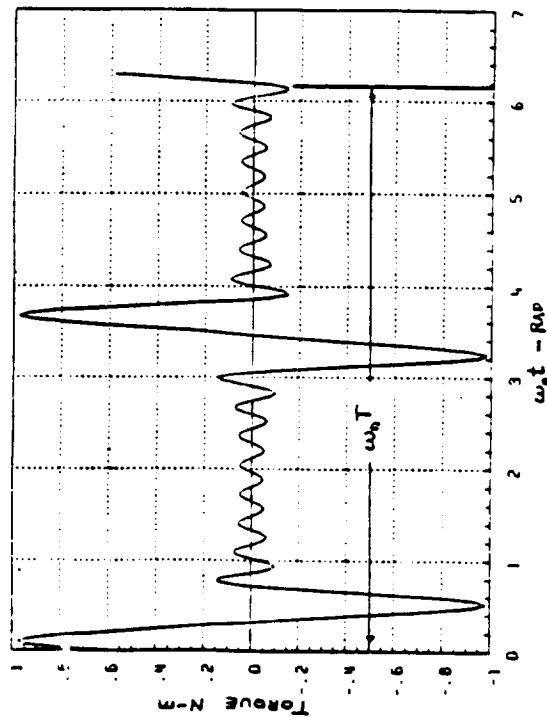
### **Structural Excitation**

A torque forcing function was generated to investigate the dynamic response of the telescope spider support structure and give a basis for deciding the need for a reactionless chopper system. The first nineteen modes of a unit pulse torque function (as described earlier in the discussion of transition trajectories) were computed. A verification of the time response representative of the 19 modes is shown. A NASTRAN structural model will provide the transfer function to compute angular misalignments and decenter at the chopper mounting location.

# STRUCTURAL EXCITATION

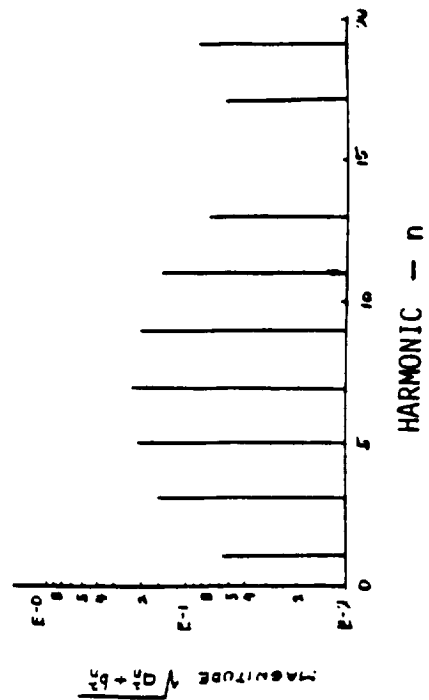
## Harmonic Content of Chopper Unity Torque Function (80% Duty Cycle)

### First 19 Modes



n	a <sub>n</sub>	b <sub>n</sub>
1	1.710E-2	-5.263E-2
3	1.247E-1	-9.062E-2
5	2.205E-1	0.000E 0
7	1.958E-1	1.423E-1
9	6.727E-2	2.071E-1
11	-4.857E-2	1.495E-1
13	-6.305E-2	4.581E-2
15	0.000E 0	0.000E 0
17	4.821E-2	3.503E-2
19	2.812E-2	8.654E-2

$$f(t) = \sum_{n=1}^{\infty} a_n \cos 2\pi n t + b_n \sin 2\pi n t$$



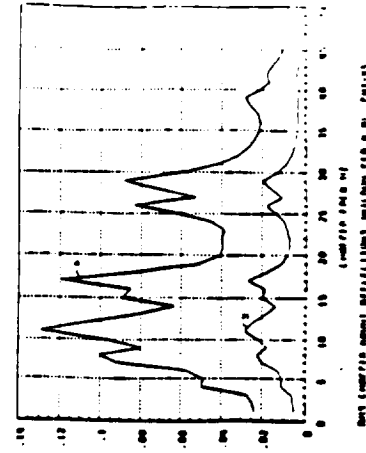
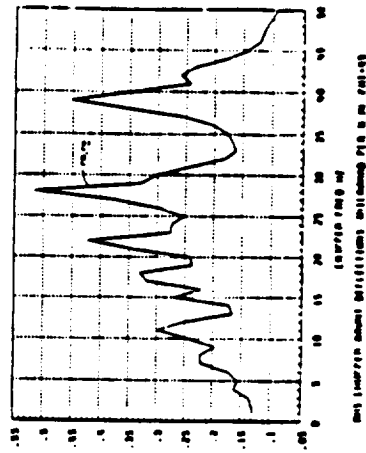
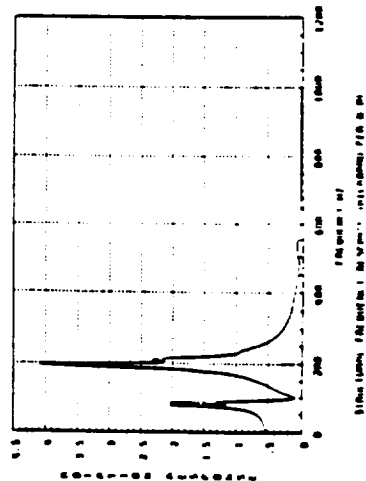
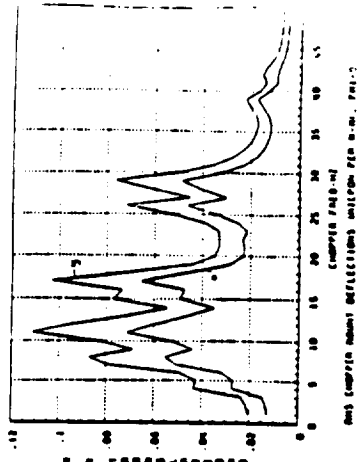
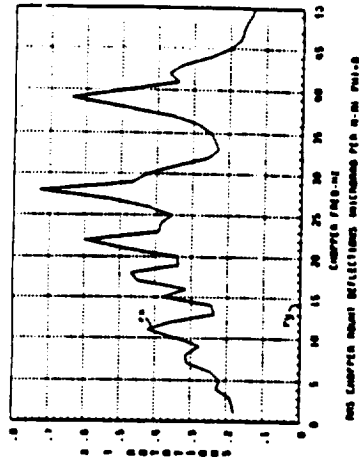
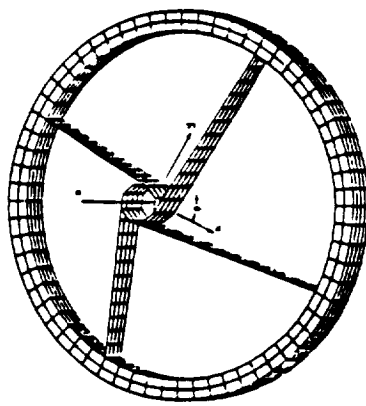
#### Structural Excitation of Chopper Mount, Spider and Heading

A NASTRAN model of the chopper mount and spider structure provided frequency response data which were useful in determining the deflections of the structure. The frequency response shown in the lower left hand plot indicates the magnitude of x-rotation (delt) as a function of a unit amplitude torque about the x-axis. Resonances near 80 and 200 Hz are apparent.

The response of the structure as a function of chopper frequency is represented as RMS deviations in rotation and decenter for an excitation axis angle of PHI=0 and 45 degrees, as indicated by the four graphs to the right.

Responses were calculated by taking the Fourier components of the unit torque function and scaling the fundamental and harmonics according to the chopper frequency. The resulting harmonic sequence was then multiplied by the transfer function and then converted back to the time domain. RMS chopper mount deflections were then computed from the time series.

### STRUCTURAL EXCITATION OF CHOPPER MOUNT, SPIDER AND HEADING



## Jitter Results

Expected maximum torques are computed for the original SOFIA specifications by assuming a mirror MOI of .015 Kg-m<sup>2</sup> and using the previously computed torque chart.

A conservative estimate for jitter is obtained by selecting the highest peaks of the response curves on the previous page and scaling them by the computed torques.

The jitter estimates are close to the levels allowed in the optical error budget. With minor structural changes, the jitter values could possibly be reduced to very conservative levels so that the use of a nonreactionless chopper can be seriously considered.

## STRUCTURAL EXCITATION

<u>Specification</u>	<u>Frequencies</u>	<u>Throw</u>	<u>Rise Time</u>	<u>MaxTorque</u>
1	1-35 Hz	5 arcmin	5msec	5.5 N-m
2	1-10 Hz	20 arcmin	7msec	11.4 N-m

## JITTER RESULTS

	<u>Jitter</u>	<u>Error Budget</u>
Rotation	Spec.1 Spec.2	3.9 $\mu$ Rad 4.6 $\mu$ Rad
Decenter	Spec.1 Spec.2	.77 $\mu$ m 1.1 $\mu$ m

## **Reactionless Concepts**

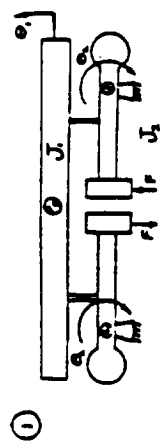
Three concepts for reactionless designs are noted here:

Concept one may have several different geometries, but the essence of the design is the fact that a contrarotating mass has been mechanically linked to the mirror with some gear or lever system in such a way that its displacement is in proportion to that of the mirror. The reaction masses and gear ratios are carefully chosen so that the net angular momentum is always zero. This concept is unique in that, if desired, the center of the mirror need no longer be constrained by a pivot point. This allows the possibility of dithering the focus by small amounts along the optical axis. The lever arrangement in (1) is particularly useful in a two-axis design where 3 or 4 arms may be arranged in a radial fashion. A candidate Lockheed design utilizes three rocker arms. Even with three arms, the angular momentum from a closer look at the practicality of such a device. The levers add complexity to the design and introduce the possibility of too much compliance in the system. Care would have to be taken to make the mechanism extremely stiff and well damped. Also, additional torque is required to move the lever arms.

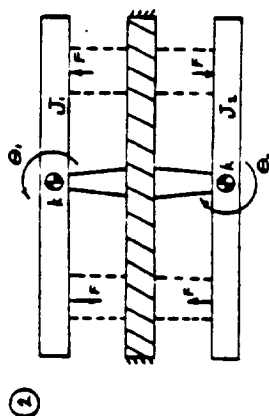
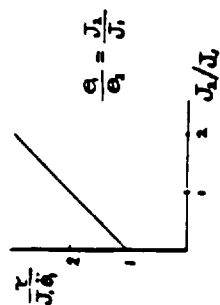
Concept two is an obvious solution to the problem; however, twice as many actuators are required and care must be taken to ensure perfect synchronization between the two inertias. The Kitt Peak chopper design is of this sort, however the designers found it difficult to implement in a two-axis version. Apparently, difficulties were encountered in precisely locating the axis of rotation at the center of mass of the mirror and reaction mass. Even slight misalignments substantially degrade the performance.

The third concept was implemented in a single-axis form with great success by the designer of the Palomar chopper. In this arrangement, the same actuation torque is required as for its nonreactionless counterpart, regardless of the size of the reaction inertia. However, the reaction inertia should be made as large as possible to limit the required stroke of the actuators. A flex pivot gimbal system suspends both the mirror and the reaction masses at precisely their centers of gravity. The natural momentum compensation. This design offers the option of interchanging the mirror because precise matching of the mirror inertia with the reaction inertia is not required.

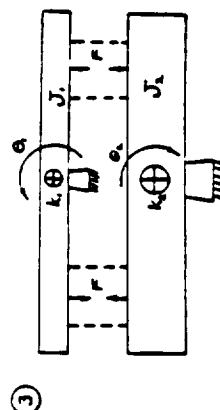
### REACTIONLESS CHOPPER CONCEPTS



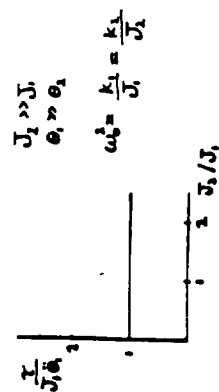
MOMENTUM BALANCE  
WITH LEVERS



DYNAMIC IMAGE



REACTION MASS



## Existing Chopper Systems

### Multiple Mirror Telescope (MMT)

There are actually several secondaries which are designed to chop in perfect synchronization at this facility. In order to achieve this capability, a fairly straightforward single-axis chopper was conceived. A low moment of inertia mirror made of fused silica makes it possible to achieve the relatively fast rise time of 3 msec. The control engineer claimed that the average power at the actuators was much less than 50 watts, but could not recall the exact figure. He did not recommend designing a home-built actuator, as they did, because of the complexity of this task. Rather, use of commercially available rare earth voice coil actuators is encouraged (Kimco, Ling, Schaeffer Magnetics, etc.). The low MOI and fairly rigid telescope structure made a reactionless design unnecessary.

The control system is a very simple analog type I design which incorporates velocity feedback. The designer recommends avoiding velocity sensors and instead differentiating the position signal. In practice, the researchers prefer to accept a small amount of overshoot (less than 5%) in trade for a fast rise time (0-100%). A major problem to overcome was that of too much compliance in the system. Very stiff flexures at the motor-mirror junctions are used.

### Kitt Peak National Observatory (KPNO)

This larger diameter (40 cm) chopper is a two-axis unit which performs quite well at a rise time of 3 msec. In order to keep the MOI from being too large, the mirror was lightweighted by cutting the mirror in half, machining out material, and bonding it back together. The chopper was originally conceived to be a reactionless design utilizing a duplicate reaction mass actuated by the same signal, however problems occurred with internal structural resonances and imprecise rotation, and true reactionless performance was not realized. The design was abandoned. The designer feels that it is not worth the effort to attempt a two-axis reactionless design.

The main center flexure is a fairly large gimbal arrangement which utilizes flex pivots. Because it is quite bulky, the mirror is forced to rotate slightly behind its center of mass. Stiffness in the motor-mirror coupling was a problem. A 400 Hz resonance problem was successfully reduced by the use of a notch filter. Moving coils attached to the mirror were used; however, moving magnets are recommended by the designer to reduce heat transfer problems and provide for a stiffer coupling arrangement.

The designer recommends an all analog control system because of its simplicity. A type II servo system was used and achieved a bandwidth of about 200 Hz. Contrary to MMT, velocity sensors are recommended. About 20 watts average are dissipated at the actuators.

### EXISTING CHOPPER SYSTEMS

LOCATION	MIRROR AMPL. P-P (ARC/MIN)	TRANSITION TIME (MSEC)	FREQUENCIES (HZ)	MIRROR MATERIAL & DIAM. (CM)	MIRROR MASS (KG) MOI (KG-M <sup>2</sup> )	ACTUATOR TYPE FORCE & NO.	CHOPPER CONFIGURATION
NMT	2.1 5	3 (0-100%)	30 7.5	CORNING 2 7940 FUSED SILICA 22.8 1.87 @ CENTER .97 @ EDGE	1.3 1.0045	CUSTOM-MADE RAPE-EARTH VOICE COIL 2	SINGLE AXIS
KPNO	2 32	3	30 11	ZERODUR 40.6 3.8 @ CENTER 1.9 @ EDGE	3-5 ? .09	CUSTOM-MADE MOVING COIL .68 (N-M)/AMP 4	DUAL AXIS REACTIONLESS ATTEMPT
PALOMAR	3.3 16.7 53	1.2 (10-90%) 1.8 3.5	83 55 28	BERYLLIUM 25.4 10.2 HOLE	1.2 .0062	COMMERCIAL ? VOICE COIL 10.4 N/AMP /ACT. 2	SINGLE AXIS REACTIONLESS >99% EFFECTIVE
UKIRT	72	7.5	- 0-15	ALUMINUM 75 3 THICK PLUS FRAME	7.5 ?	LING SHAKERS VOICE COIL 4	DUAL AXIS
LSMC	3.5	3.2 (10-90%)	10	ZERODUR 40.6 5 THICK	9 1.09	CUSTOM-MADE ELECTRODYNAMIC TYPE 3	DUAL AXIS REACTIONLESS 95% EFFECTIVE
IDEAL SOFIA	5 20 40 MAX	5 7	1-35 1-10	TBD 30.5 2.5 THICK	TBD	TBD	DUAL AXIS REACTIONLESS IF NECESSARY

## Palomar

This very successful single-axis reactionless design uses a thin Beryllium mirror to achieve a low MOI. This very stiff system has virtually no inertial resonance problems. The voice-coil actuators are mounted on a much higher MOI reaction mass which is also suspended by flex pivots. Stiff flexures attach the actuator to the mirror.

Successful reactionless performance is achieved even beyond 80 Hz and researchers are able to operate the chopper at any desirable frequency. The designer estimates that torques on the order of .1% are transferred to the structure. He admits, however, that a two-axis system would be much more difficult to construct because of the added difficulty in making a stiff two-axis gimbal. He recommends using as high a reaction mass MOI as possible. The control system is a very simple lead/lag type I design. No velocity sensors were used.

## United Kingdom Infrared Telescope (UKIRT)

This is a very large system for the James-Clark-Maxwell mm Telescope. The very large diameter (75cm) and thin (3mm) aluminum mirror is rigid enough by virtue of its high parabolic profile and support by a stiff rim. Four large (30 cm long) Ling Shaker motors are used. Motor-mirror couplings are essentially 3mm wires which are tightly clamped and provide enough stiffness to perform well. The control system is the only digital design which was encountered. A 6809 microprocessor executed a very sophisticated adaptive control algorithm.

## Lockheed Missiles and Space Company (LMSC)

This large mirror fast pointing system was not designed specifically as a chopper, but incorporates some unique ideas which might be suitable for a two-axis reactionless chopper. This is the only design investigated which doesn't use a voice-coil type actuator. The so-called electrodynamic actuators are really rocker arms which operate like a segment of a series-wound motor. The designer takes advantage of the angular momentum of the rocker arms to compensate for the angular momentum of the mirror, resulting in a thin reactionless design concept. Three of these arms support the mirror from behind without the use of a center gimbal arrangement. A 95% reactionless performance is claimed. Although in the present design the actuators extend beyond the mirror periphery, the designer claims that they can easily be designed to fit completely behind the mirror. This unit has the possibility of focusing and dithering, as well as chopping, with the same mechanism. The rocker mechanisms are quite complicated however, and the cost of producing such a design may be significantly higher than others. The control system incorporates an analog type I PID controller with only position sensors. A microprocessor generates position, velocity and force trajectories. By using velocity and force feedback, a very accurate trajectory can be followed, virtually eliminating any overshoot.

## EXISTING CHOPPER SYSTEMS (CONTD)

LOCATION	CHOPPER SIZE ENVELOPE	FLEXURE STYLE	SENSOR TYPE	OPERATING CURRENT VOLTAGE (AMPS,VOLTS)	CONTROLLER TYPE/COMP
MMT	22.8cm x 7.6cm w/o focusing	FLEX PIVOTS	(POS) SCHAEVITZ & HP LVDT'S, (VEL) MOVING COIL	10 24	ANALOG LEAD/LAG
KPNO	40.6 x 7.6 w/o focusing	BENDIX FLEX PIVOTS, U-JOINT CONFIGURATION	(POS) SCHAEVITZ LVDT, (VEL) SCHAEVITZ	8 48	ANALOG LEAD/LAG TYPE 2
PALOMAR	25.4 x 15.2 w/o focusing	FLEX PIVOTS	(POS) SCHAEVITZ LVDT (VEL) DERIVED FROM POS	?	ANALOG LEAD/LAG
UKIRT	75.0 x 40 w/o focusing	FLEX PIVOTS	(POS) LVDT TYPE (VEL) ?	22/ACTUATOR 24	DIGITAL ADAPTIVE 6809 $\mu$ P
LSMC	40.6 x 22.3 w/o focusing	MIRROR UNSUPPORTED AT CENTER, FLEXURES AT ACTUATOR PIVOT	(POS) ? (VEL) DERIVED FROM POS	48 28	ANALOG PID TYPE 1
IDEAL SOFIA	30.5 x 35.5 w/focusing	TBD	TBD	TBD	TBD

### Conclusions and Recommendations

- Expend a reasonable effort to reduce the moment of inertia of the secondary mirror.
- Experience of others indicates that internal structural resonances cause severe jitter problems. Care should be taken to resolve this problem by:
  - Keeping the mechanism simple
  - Paying particular attention to the stiffness of the motor-mirror juncture
  - Using a voice coil configuration which eliminates the motor-mirror flexure
- A simulation which includes the flexibility of the motor-mirror juncture indicates that there is a significant advantage gained in controlling the chopper if velocity feedback is taken from the motor rather than at the mirror. Position feedback should be taken from the mirror.
- Structural calculations indicate that a reactionless system may not be a requirement. Preliminary results show that jitter may be very close to the allowable amount.

### Conclusions and Recommendations (Contd)

- To keep the chopper mechanism simple, a separate focus dither mechanism is recommended.
- Analog compensators have proven to be adequate for chopper control. Digital control is possible.
- Accurate tracking of the desired transition profile is desirable to minimize the torque required and keep the electronics and actuators from saturating.
- Assuming that Image Motion Compensation is not a requirement, a single-axis chopper with rotation may be adequate, and can be designed with existing technology.
- A two-axis design is also feasible with the added complexity of ensuring that the axes of rotation are true. A reactionless two-axis system may be difficult to design.
- Should a reactionless design become a firm requirement, a single-axis design based on the "Reaction Mass" concept is recommended in view of the success obtained with the Palomar chopper system.

## **SOFIA Telescope Structure**

### **Scope**

The SOFIA telescope structure includes all structural elements that are inertially isolated from the aircraft pitch, yaw, and roll movements. The structure elements falling within this category are described as follows.

The telescope supporting structure is referred to as the centerpiece. It is that portion of the structure that the telescope is mounted on/in, and is the primary structural element of the telescope system.

The primary mirror supporting structure is that portion of the structure that the primary mirror is mounted to, and connects the primary mirror to the metering structure.

The metering structure is referred to as the metering tube since the current concept is a large tube. The metering tube connects the primary and secondary mirror supporting structures to each other. The metering tube is supported by the centerpiece structure.

The secondary mirror support structure is that portion of the structure which mounts secondary mirror and chopper. This includes the heading and spider assembly.

The instrumentation and counterweighting support structure is referred to as the instrumentation flange. The instrument flange is the structure that supports instrument packages in the Nasmyth configuration, and supports counterweights for the balanced design.

The airbearing shell and connecting structure are defined to be the outer spherical shell of the airbearing and the cylindrical connecting structure between the instrument flange and the airbearing, and between the centerpiece and the airbearing.

Excluded from this scope is the stator portion of the airbearing and the vibration isolation system, which are described in Section 4.3. The primary mirror support structure is addressed at the end of this section (4.2).

## **SOFIA TELESCOPE STRUCTURE - SCOPE**

- TELESCOPE SUPPORT STRUCTURE/CENTERPIECE
- PRIMARY MIRROR SUPPORT STRUCTURE
- METERING STRUCTURE (TUBE)
- SECONDARY MIRROR SUPPORT STRUCTURE/HEADRING AND SPIDERS
- INSTRUMENTATION AND COUNTERWEIGHTING STRUCTURE/INSTRUMENT FLANGE
- AIRBEARING SPHERICAL SHELL AND CONNECTING STRUCTURE

### **SOFIA Telescope Structure-Major Requirements**

**There are three major requirements for the SOFIA telescope structure, weight, size, and stiffness or dimensional stability.**

**The entire telescope system has been given a weight budget of 30,000 lbs. The telescope structure as defined in the scope represents approximately 2/3 of the telescope system. Therefore, the telescope structure should not weigh more than 20,000 lbs, including the weight of the primary and secondary mirrors.**

**The physical size of the telescope structure must be large enough to rigidly support optics for a 2.75-3.0 m f/l telescope. However, the size of the structure must fit within the available aircraft cavity volume including all desired movements of the telescope.**

**The telescope structure must have a first mode natural frequency that is high enough to avoid structural resonance induced by cavity wind loads or aircraft vibrations. The high first mode is also necessary to avoid instability problems in the pointing control system.**

**The telescope structure must have very high dimensional stability so movement of optical components mounted in the structure will be within values specified for the error budget. This includes de-focus, de-center, and de-tilt of the secondary mirror relative to the primary under gravity, dynamic and temperature loads.**

### **SOFIA TELESCOPE STRUCTURE - MAJOR REQUIREMENTS**

- **WEIGHT:**  
TELESCOPE STRUCTURE INCLUDING THE OPTICS NOT TO EXCEED THE WEIGHT BUDGET
- **SIZE/VOLUME:**  
TELESCOPE STRUCTURE MUST BE LARGE ENOUGH TO SUPPORT 2.75-3M OPTICS AND COMPACT ENOUGH TO FIT IN AIRCRAFT CAVITY
- **STIFFNESS/RIGIDITY:**  
FIRST MODE NATURAL FREQUENCY MUST BE HIGH ENOUGH TO AVOID RESONANCE AND CONTROL PROBLEMS  
MOVEMENT OF OPTICAL COMPONENTS MUST BE WITHIN LIMITS OF ERROR BUDGET

### SOFIA Telescope Conceptual Design

The conceptual layout of the SOFIA telescope system is modeled on the KAO. As a result, the concept for the SOFIA telescope structure follows the KAO telescope as well.

The centerpiece is the main supporting structure for the telescope. It is a welded or bonded plate structure as in the KAO design, except that the plates have varying thickness. This type of design provides a very stiff structure with minimal weight.

The metering structure for the SOFIA telescope is a tube and not a truss as on the KAO. The metering tube extends through the centerpiece and is rigidly mounted to the top surface of the centerpiece. However, it is mounted to the bottom surface of the centerpiece such that movement of the metering tube relative to the centerpiece is allowed in the axial direction only. This allows the centerpiece to be constructed of materials with a high coefficient of thermal expansion such as aluminum.

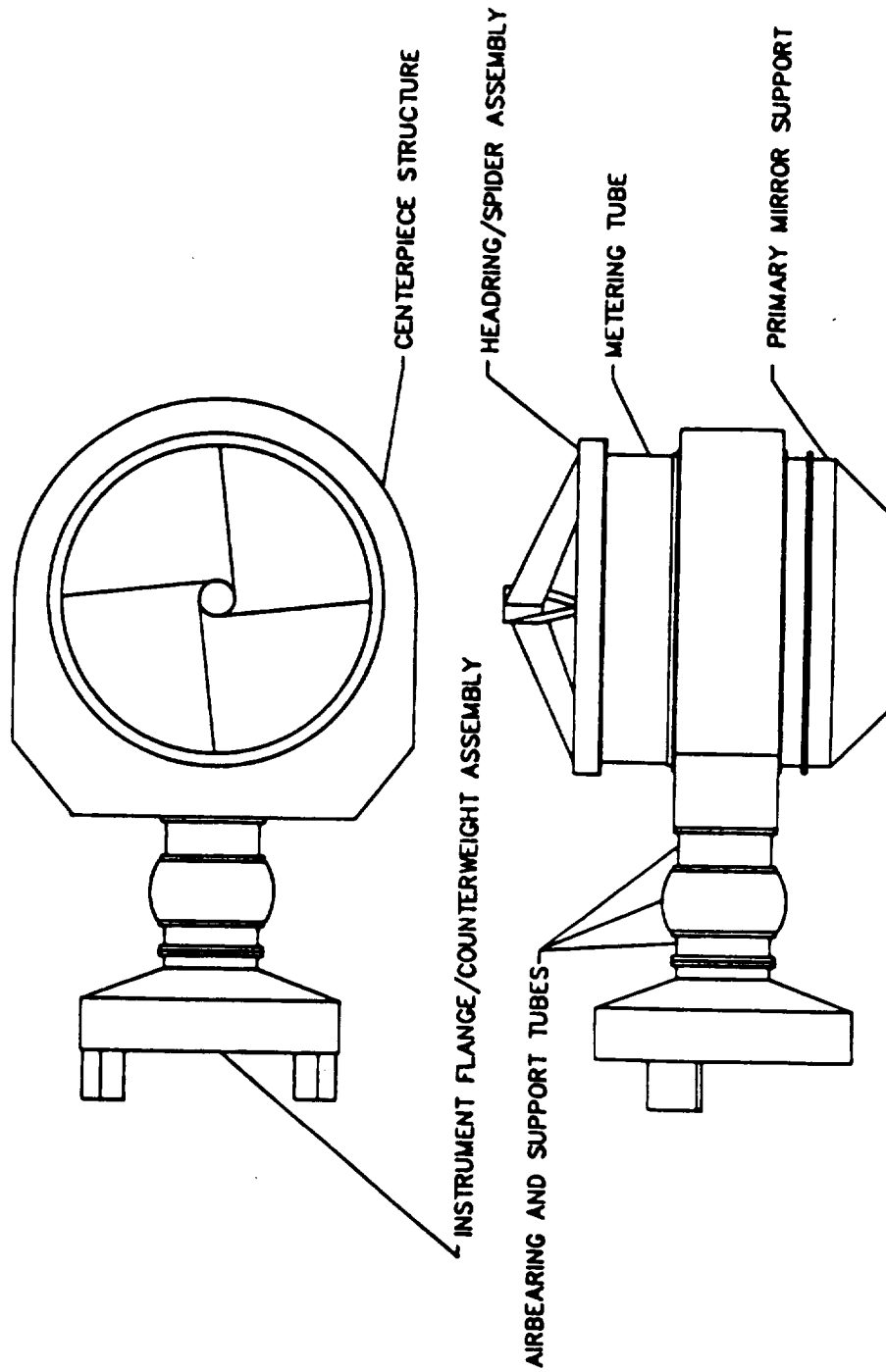
The primary mirror support is a bonded plate structure. This is again done to provide a light, stiff structure. The primary mirror support is mounted to the bottom of the metering tube with a flange arrangement to facilitate removal of the primary mirror.

The heading and spider assembly is a box section ring with flat plate spiders supporting secondary mirror/chopper. The assembly is not flat as is conventional, but is crowned so that the top of the heading is lower than the secondary mirror. This is necessary for clearance in the aircraft cavity. The heading is mounted to the top of the metering tube with a flange arrangement to facilitate removal.

The instrument flange is also a welded plate structure. The instrument flange does not have to be designed for lightness since it provides some counterweighting itself as in the KAO. However, the majority of counterweighting is provided with movable weights located on the lugs. This allows the structure to be balanced about the center of the airbearing with less weight overall.

The instrument flange and centerpiece are connected to the airbearing structure with flange interfaces. The airbearing sphere is considered to be a spherical shell for the purposes of structural analysis.

## SOFIA TELESCOPE STRUCTURE CONCEPTUAL DESIGN



### Components of Structural Analysis Model

For structural analysis of the telescope, a finite element model was created for analysis with NASTRAN. The model consists of five major components: the centerpiece; metering tube, heading and spider assembly; the primary mirror support; the airbearing shell and connections; and the instrument flange. The components are separated this way because each component was developed independently and added to the structure in the order listed.

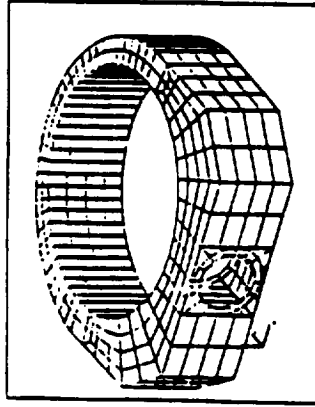
The centerpiece is modeled as an aluminum plate structure with internal stiffeners. The plate ranges from 2.25 to 0.045 inches thick. This was done using an optimization routine to keep the first mode natural frequency as high as possible while minimizing the weight.

The metering tube and primary mirror support are modeled as plate structures with the material being graphite epoxy composite and honeycomb sandwich. The material will be discussed in more detail elsewhere in this report. The heading is a box section ring and is modeled with 1-inch thick flat plate, as are the spiders. The material for heading and spiders is modeled as graphite epoxy composite with the same layup as for the sandwich material.

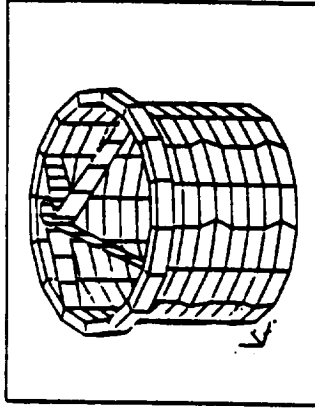
The airbearing and connecting structure are modeled as 2 inch thick Invar plate. The spherical shell was found to have more than sufficient stiffness, so no internal structure was assumed for the airbearing sphere.

The instrument flange is modeled as an aluminum plate structure with internal stiffeners. The plate is 2 inches thick. No attempt is made to reduce the weight of the instrument flange since it acts as part of the counterweight.

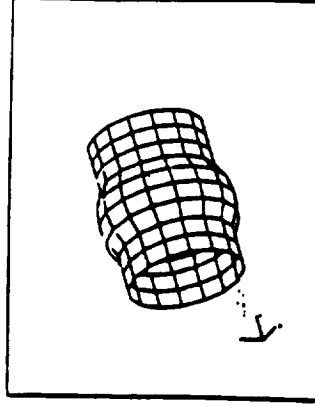
## COMPONENTS OF STRUCTURAL MODEL



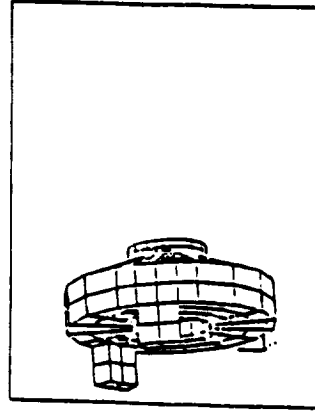
CENTERPIECE



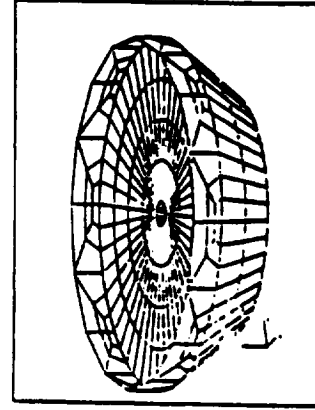
METERING TUBE  
HEADING/SPIDER



AIRBEARING SHELL



INSTRUMENT FLANGE



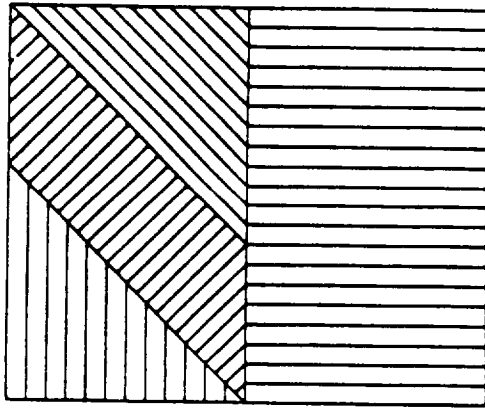
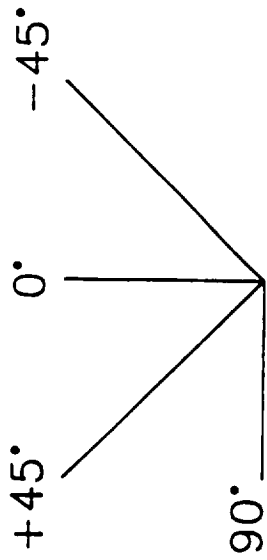
PRIMARY MIRROR SUPPORT

#### Honeycomb Core Composite Sandwich Model

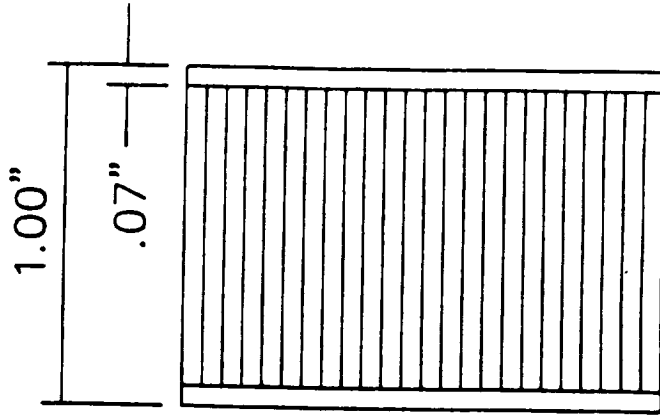
The composite sandwich material that was used extensively for modeling components of the telescope structure was chosen in part to take advantage of unequal coefficients of thermal expansion as well as low thermal expansion and weight.

The ply lay-up was chosen to try and match the coefficient of expansion of the aluminum centerpiece in the radial direction and have a coefficient close to zero in the perpendicular direction. A basic set of 0, +45, and 90 degree orientations were chosen for ply directions. Then the number of plies in each direction was chosen to match the desired thermal expansion. The material model that was used does not currently meet the requirements, and ply orientations other than 0, +45, and 90 should be used in future design efforts.

## HONEYCOMB CORE COMPOSITE SANDWICH MODEL



8 PLYS  $\bullet$   $0^\circ$   
 4 PLYS  $\bullet$   $\pm 45^\circ$   
 2 PLYS  $\bullet$   $90^\circ$



### Integrated Structural Model

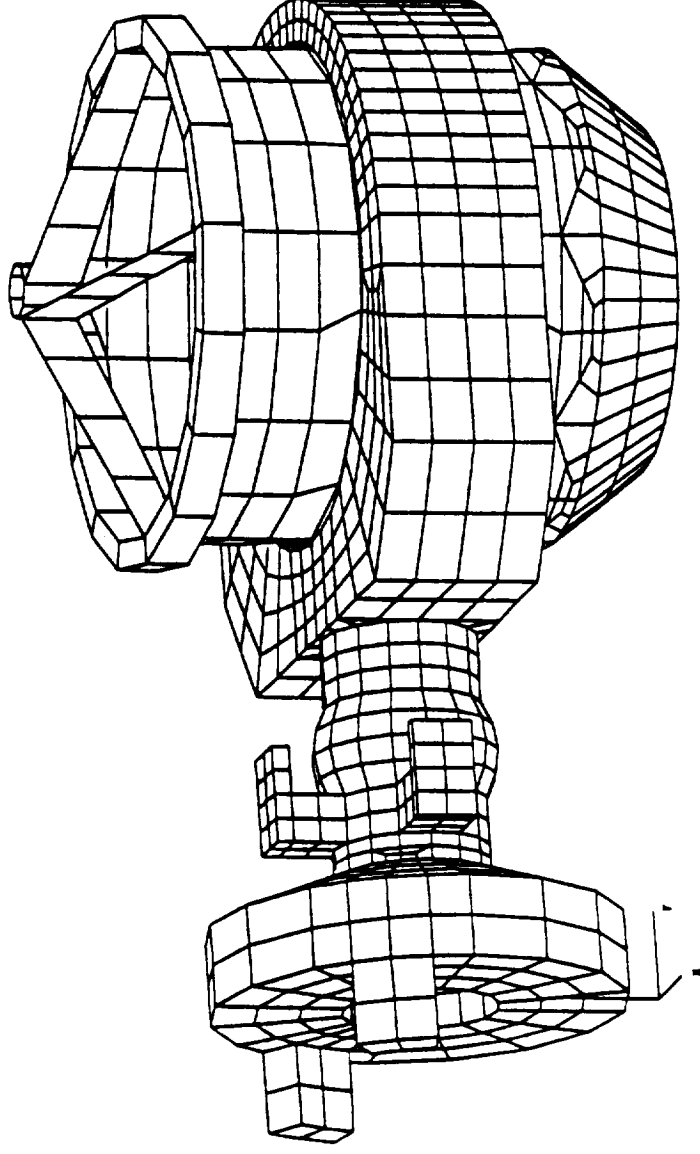
The integrated structural model is made up of the components discussed previously. All of the components are rigidly meshed together except for the bottom centerpiece to metering tube connection. This connection allows translation of the metering tube relative to the centerpiece in the vertical (or z) direction.

The primary mirror mass is modeled as a concentrated mass with principal moments of inertia included. The mirror weight is distributed to points on the primary mirror support with a rigid body element that adds no stiffness to the structure.

Other concentrated masses are used to represent the secondary mirror, tracker telescope, and counterweights.

It should be noted here that the integrated model shown here includes the torquer mounts. Although these are not included in the scope of this discussion, they were necessary for determining the control system response between the torquers and guidance gyros and tracker telescope.

## INTEGRATED STRUCTURAL MODEL



### Analysis of Telescope Structure

Analysis of the telescope structural model was done using NASTRAN. The types of analysis performed were normal modes, deflections under gravity, dynamic loads, temperature loads, and additional analysis for chopper and control system design investigations.

The normal modes analysis was done to determine all modes and their deflected shapes under 100 Hz. The first mode frequency is a measure of structural stiffness. The other modes are useful for predicting pointing control response and structural resonance problems.

A static load consisting of a gravity force was applied with the structure oriented at elevation angles of 20 to 60 degrees. This was done to investigate the stability of the secondary mirror de-focus, de-center, and de-tilt relative to the primary mirror as a function of telescope elevation.

A dynamic load using a sinusoidal forcing function with a .25g amplitude at a frequency of 1Hz was applied to the structure with the telescope oriented at 40 degrees elevation. This was done to investigate secondary mirror jitter in de-focus, de-center, and de-tilt relative to the primary mirror. This loading condition is used to simulate maximum acceleration of the telescope.

A temperature load representing a 25 degree F change in temperature was applied to the entire structure. This was done to investigate stability of secondary mirror de-focus, de-center, and de-tilt relative to the primary mirror as a function of temperature fluctuations.

Analysis was done on the telescope structure in support of other system analysis as well. The transfer function between torquer locations and guidance gyro and tracker telescope locations was determined to help pointing control analysis. Also, frequency response of the heading and spiders to secondary chopper input torques was determined. This was done to determine if and to what degree a reactionless chopper would be necessary.

## **ANALYSIS OF SOFIA TELESCOPE STRUCTURE**

- NORMAL MODES ANALYSIS
- STATIC/GRAVITY LOAD OVER 20° TO 60° ELEVATION RANGE
- DYNAMIC LOAD OF .25g ACCELERATION AT 1 Hz
- TEMPERATURE LOAD FOR A 25° F CHANGE
- ADDITIONAL ANALYSIS FOR OTHER SUBSYSTEMS STUDY

#### Telescope Structure Goals and Parameters

The goals and parameters are derived from the major requirements, and specific alignment requirements for the telescope optics.

The goal weight of the structure is 20,000 lbs, including the optics. This is approximately 2/3 of the weight budget for the telescope system as described in the major requirements.

The first mode natural frequency goal of 25 Hz was set after initial models showed that values significantly higher than this would not be attainable within weight and size restrictions for the structure.

The parameters for de-focus, de-center, de-tilt, and line of sight were determined from error budget limits set by the optical design.

### **TELESCOPE STRUCTURE GOALS AND PARAMETERS**

<b>ITEM</b>	<b>GOALS/PARAMETERS</b>
<b>WEIGHT OF STRUCTURE INCLUDING OPTICS</b>	<b>20,000 LBS</b>
<b>FIRST MODE NATURAL FREQUENCY</b>	<b>25 Hz</b>
<b>SECONDARY TO PRIMARY DE-FOCUS, STABILITY LIMIT</b>	<b>5 MICRON</b>
<b>SECONDARY TO PRIMARY DE-CENTER, ABSOLUTE LIMIT</b>	<b>50 MICRON</b>
<b>SECONDARY TO PRIMARY DE-CENTER, JITTER LIMIT</b>	<b>1 MICRON</b>
<b>SECONDARY TO PRIMARY DE-TILT, ABSOLUTE LIMIT</b>	<b>60 ARCSEC</b>
<b>SECONDARY TO PRIMARY DE-TILT, JITTER LIMIT</b>	<b>.5 ARCSEC</b>

### Results of Normal Modes Analysis

The lowest modes of interest are the 4th, 5th, 7th, and 8th natural frequencies for the structure. The first three were excluded because they are rigid body modes that result from allowing rotation about the three axes, and 6th because it involves only localized movement in the structure.

The lowest natural frequency for the structure is 27.1 Hz. The mode shapes for the four modes of interest are described below.

The 4th mode, at 27.1 Hz, is a lateral dumbbell mode. It is so described because the structure takes on a dumbbell shape, bending laterally about the airbearing sphere.

The 5th mode, at 27.5 Hz, is a vertical dumbbell mode. In this mode the secondary spiders extend upward in the same direction of travel as the telescope.

The 7th mode, at 33.4 Hz, is another vertical dumbbell mode. However, in this mode the secondary spiders extend upward in the opposite direction of travel from the telescope.

The 8th mode, at 50.8 Hz, is a twisting mode. It is so described because the structure twists about the elevation axis of the telescope.

### **NORMAL MODES ANALYSIS**

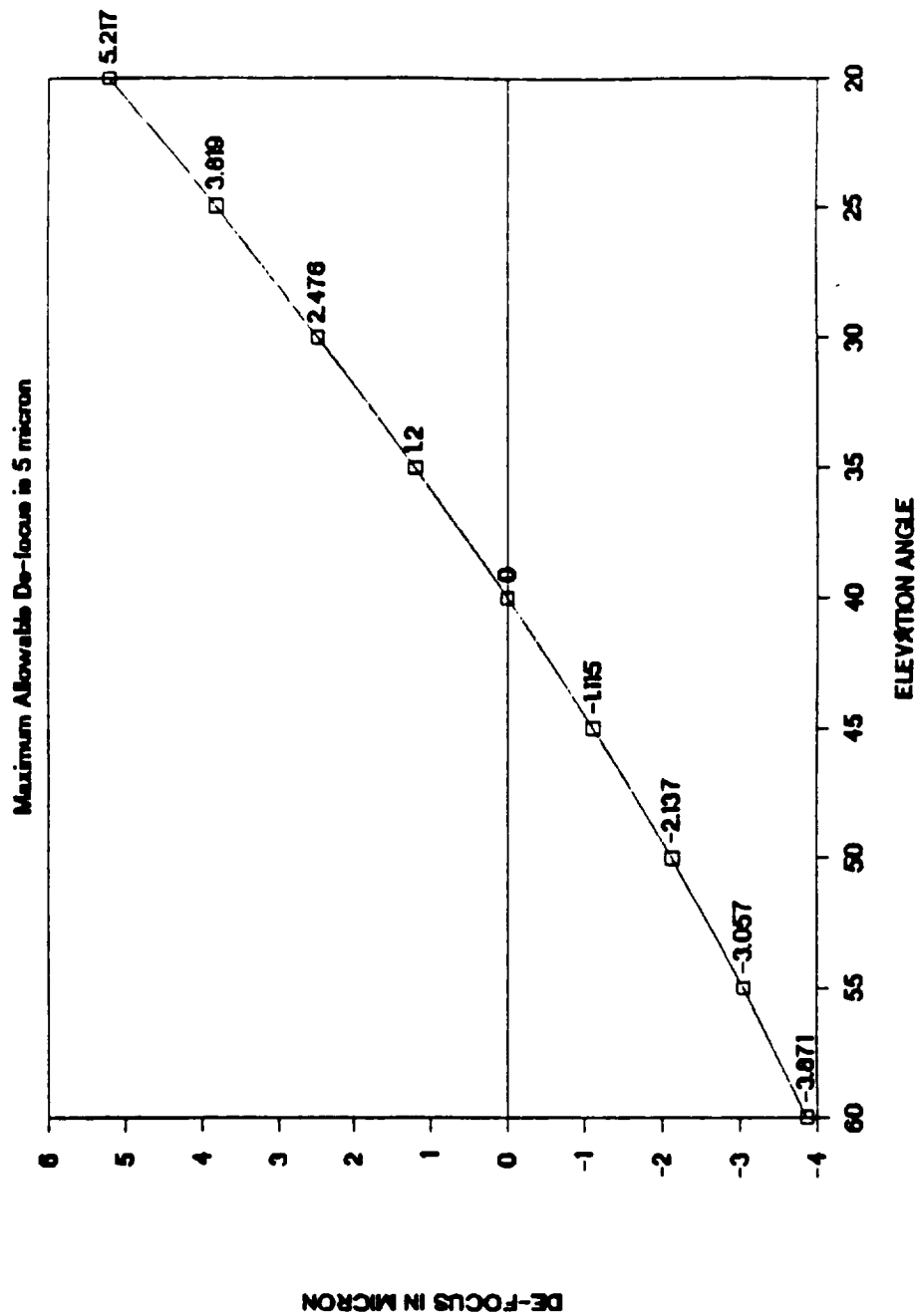
<b>MODE</b>	<b>FREQUENCY, Hz</b>
<b>4TH, LATERAL DUMBBELL MODE</b>	<b>27.1</b>
<b>5TH, VERTICAL DUMBBELL MODE</b>	<b>27.5</b>
<b>7TH, VERTICAL DUMBBELL MODE</b>	<b>33.4</b>
<b>8TH, AXIAL TWIST MODE</b>	<b>50.8</b>

(FIRST THREE MODES ARE RIGID BODY MODES; 6TH MODE HAS LOCALIZED MOTION ONLY)

### **Results for De-focus Stability vs Elevation Angle**

The de-focus vs elevation angle curve was constructed assuming that all de-focus is removed with the telescope at 40 degree elevation angle. Therefore, the curve represents a de-focus as the telescope is raised and lowered from 40°. The de-focus ranges from 3.87 microns at 60° to 5.22 microns at 20°. This represents a de-focus stability of 5.22 micron against an error budget stability limit of 5 microns.

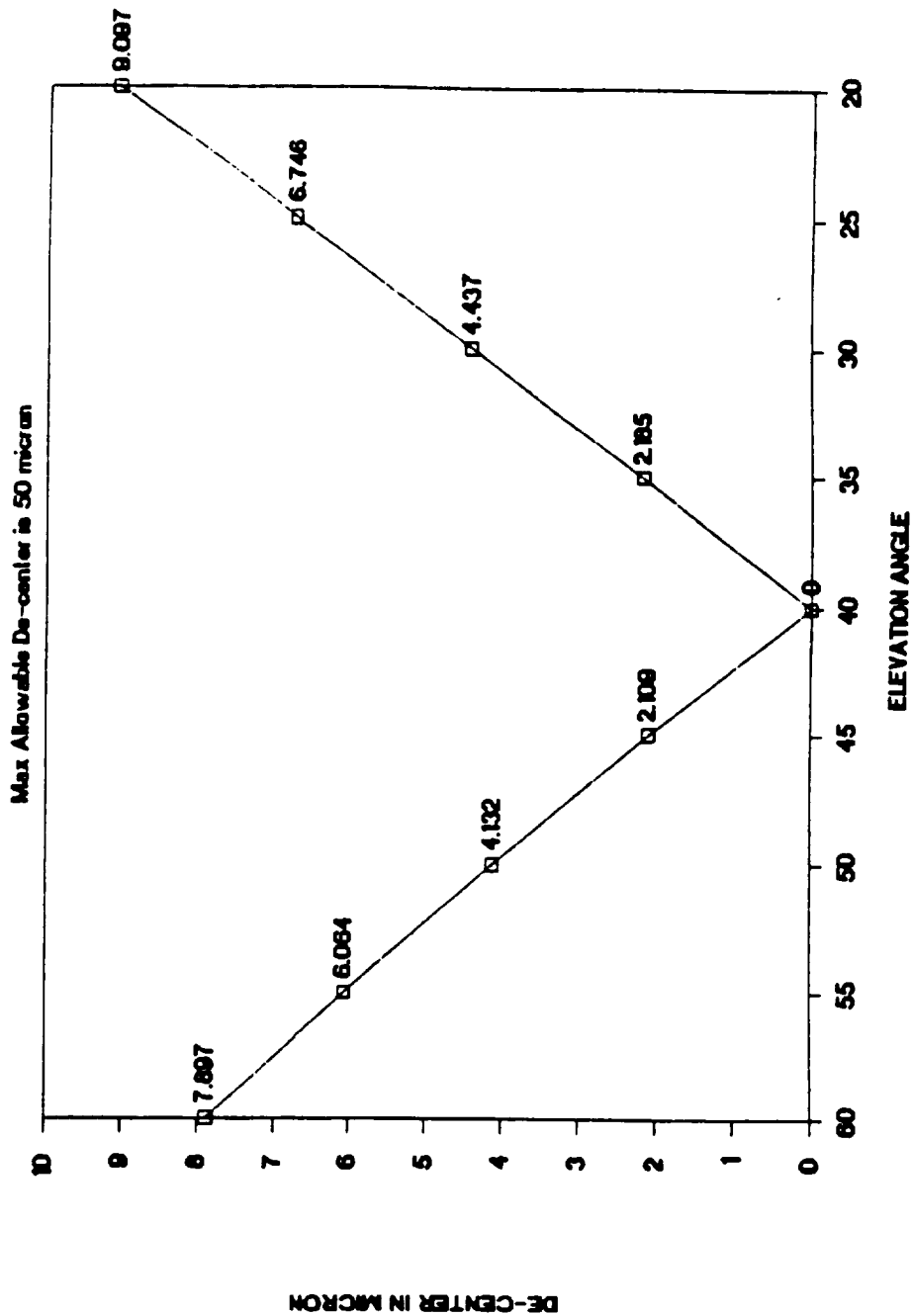
### DE-FOCUS VS ELEVATION ANGLE



### Results for De-center vs Elevation Angle

The de-center vs elevation angle curve is constructed in the same manner as the de-focus curve. The magnitude of de-center is calculated as the root sum square (RSS) for de-center in the X and Y directions, so all de-center is shown as positive. The magnitude of de-center ranges from 7.9 microns at 60° elevation to 9.1 microns at 20°. Therefore, the de-center stability due to elevation changes is 9.1 microns compared to an error budget absolute limit of 50 microns.

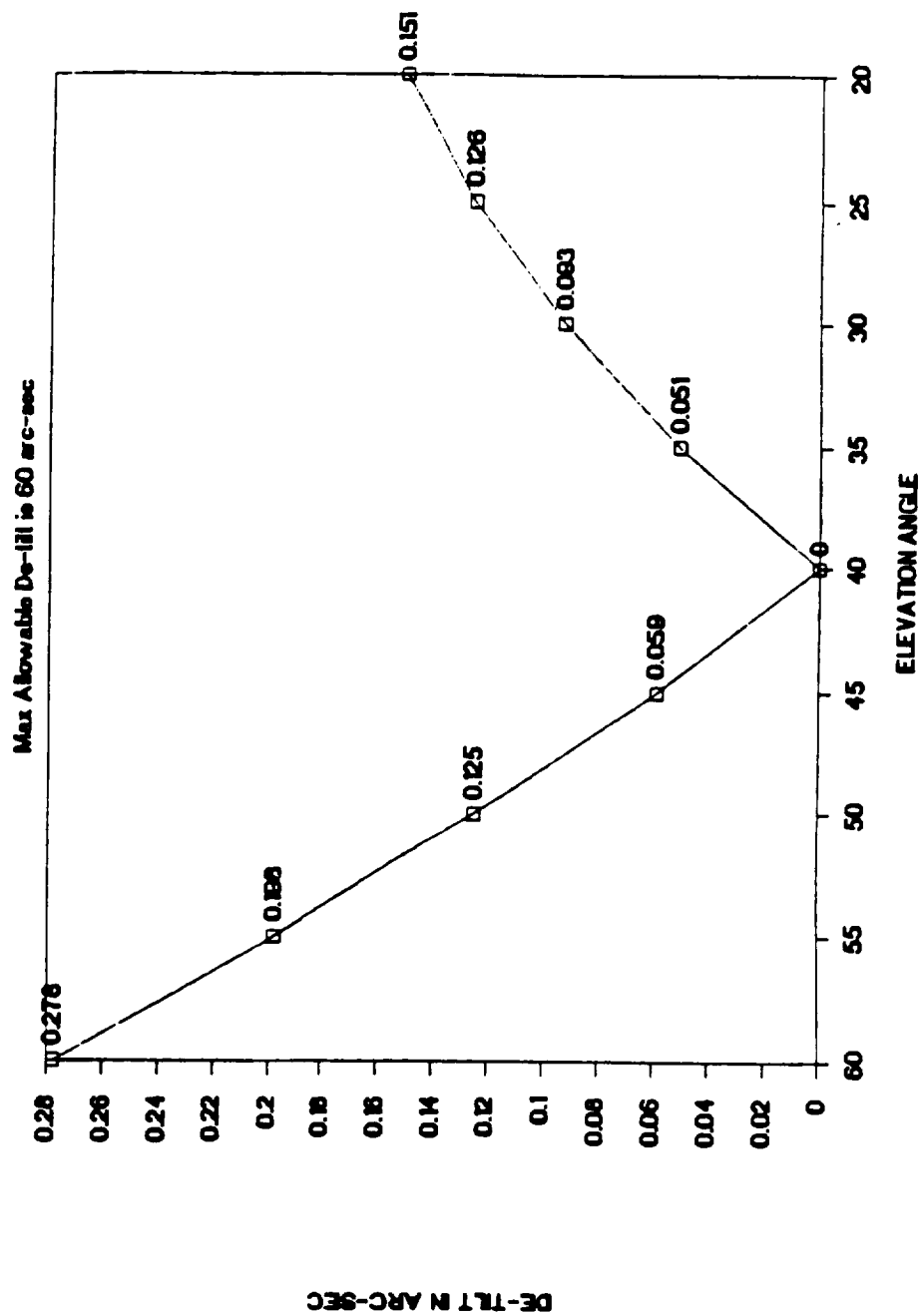
## DE-CENTER VS ELEVATION ANGLE



#### **Results for De-tilt vs Elevation Angle**

The de-tilt vs elevation angle curve is also constructed in the same manner as the de-focus curve. Also, X-axis and Y-axis de-tilt have been combined in the same manner as for the de-center curve. The de-tilt ranges from 0.28 arcsec at 60 degrees elevation to 0.15 arcsec at 20 degrees. Therefore, the stability of de-tilt due to elevation angle changes is 0.28 arcsec compared to an error budget absolute limit of 60 arcsec.

### DE-TILT VS ELEVATION ANGLE



**Results for Dynamic Load of .25g at 1Hz**

The de-focus, de-center, and de-tilt for the secondary mirror relative to the primary mirror were determined for the dynamic loading case.

The de-focus for this load is  $1.9 \times 10^{-4}$  microns compared to the error budget stability limit of 5 microns.

The de-center jitter for the dynamic load is  $9.8 \times 10^{-2}$  micron. The error budget limit for de-center jitter is 1 micron.

The de-tilt jitter for the dynamic load is  $4.36 \times 10^{-5}$  arcsec. The error budget limit for de-tilt jitter is 0.5 arcsec.

The line of sight (LOS) change due to the dynamic load is  $6.65 \times 10^{-2}$  arcsec. The jitter limit for LOS change is 0.15 arcsec.

### RESULTS FOR DYNAMIC LOAD OF .25g AT 1 Hz

PARAMETER	RESULT	STABILITY LIMIT	JITTER LIMIT
DE-FOCUS	$1.9 \times 10^{-4}$ MICRON	5 MICRON	-
DE-CENTER	$9.8 \times 10^{-2}$ MICRON	-	1 MICRON
DE-TILT	$4.36 \times 10^{-5}$ ARCSEC	-	.5 ARCSEC
LOS CHANGE	$6.65 \times 10^{-2}$ ARCSEC	-	.15 ARCSEC

ALL PARAMETERS ARE WITHIN LIMITS

#### Results for Temperature Load

The de-focus, de-center, and de-tilt of the secondary mirror relative to the primary mirror were determined for the temperature load as well.

The de-focus stability for temperature changes is 70.5 microns. The error budget limit for de-focus stability is 5 microns.

The de-center thermal stability is 8.0 microns, compared to the error budget absolute limit for de-center of 50 microns.

The de-tilt stability is 0.71 arcsec, compared to the error budget absolute limit for de-tilt of 60 arcsec.

### **RESULTS FOR TEMPERATURE LOAD OF 25°F CHANGE**

PARAMETER	RESULT	STABILITY LIMIT	ABSOLUTE LIMIT
DE-FOCUS	70.5 MICRON	5 MICRON	--
DE-CENTER	8.01 MICRON	--	50 MICRON
DE-TILT	0.71 ARCSEC	--	60 ARCSEC

DE-FOCUS EXCEEDS STABILITY LIMIT BY A FACTOR OF 16

### Telescope Structure Moment of Inertia

The moment of inertia matrix for the structure is as shown in the table. The values include the mass of the primary and secondary mirrors, counterweights, tracker telescope, and airbearing spherical shell. There is no goal value or parameter for the MOI matrix, so it is presented primarily for information. However, a relative idea of the mass distribution and pointing control torque motor requirements can be determined from the MOI matrix.

### TELESCOPE STRUCTURE MOMENT OF INERTIA

MASS AXIS	X	Y	Z
X	$1.265 \times 10^8$	$4.576 \times 10^5$	$3.846 \times 10^5$
Y		$4.232 \times 10^7$	$-1.004 \times 10^7$
Z	SYM		$1.374 \times 10^8$

ALL VALUES ARE IN UNITS OF LB-IN<sup>2</sup>

C-3.

### Telescope Structure Summary and Conclusions

The results of analysis on the structure are summarized in the following paragraphs.

The weight of the conceptual structure design, including primary and secondary mirrors, counterweights, and tracker telescope is 13,750 lbs. This does not include the weight of the airbearing spherical shell. The weight is well within the weight goal of 20,000 lbs.

The first non-zero normal mode frequency is 27.1 Hz. This is above the minimum goal of 25 Hz. It is believed that the stiffness of the structure as represented by the 27.1 Hz lowest mode is sufficient to avoid structural resonance as well as pointing control problems.

De-focus, de-center, and de-tilt are within stability limits through the full range of pointing elevations. This means that no adjustment of the optics is necessary due to large changes in pointing elevation during sighting.

De-focus, de-center, de-tilt, and line of sight are within jitter limits for dynamic loads on the structure. Therefore, the conceptual design is stiff enough to keep the optics in alignment during flight. However, this does not take into account cavity wind loads on the structure, which are still unknown.

De-center and de-tilt are within stability limits for a temperature change 20°F on the entire structure. However, the de-focus is not within stability limits for the temperature change. Therefore, the conceptual design would require re-focusing the optics during sighting if changes in cavity air temperature were encountered.

Finally, the conceptual structure design is large enough to support optics for a 3 m, f/1 telescope, and still fit within the aircraft cavity space in a static sense. The dynamic envelope of the telescope relative to the cavity volume constraint requires further investigation.

## **TELESCOPE STRUCTURE SUMMARY AND CONCLUSIONS**

- WEIGHT ESTIMATE OF CONCEPTUAL DESIGN IS 13,750 LBS NOT INCLUDING AIRBEARING SPHERE
- 1ST NON-ZERO NORMAL MODE IS 27.1 Hz
- DE-FOCUS, DE-CENTER, AND DE-TILT STABILITY LIMITS ARE MET FOR FULL RANGE OF ELEVATION ANGLES
- DE-FOCUS, DE-CENTER, DE-TILT, AND LOS JITTER LIMITS ARE MET FOR DYNAMIC LOAD
- DE-CENTER AND DE-TILT STABILITY LIMITS ARE MET FOR TEMPERATURE LOAD; DE-FOCUS LIMIT CURRENTLY NOT MET
- CURRENT CONCEPTUAL DESIGN WILL SUPPORT 3M OPTICS

## Telescope Structure Open Issues

The de-focus stability requirements for the current model can be met if the temperature change experienced by the telescope during viewing is less than 1.5°F. However, since the predicted temperature change can be as high as 20°F, more work is needed in this area to preclude possibly frequent refocusing.

There are two issues regarding temperature stability. First, the composite material used to model the metering tube and other components does not have the desired thermal expansion properties. Second, temperature loadings that represent transient state conditions as predicted by thermal analysis have not been applied to the structure.

The composite material issue is a matter of ply layup design. Although the material used for the conceptual model does not have the desired thermal properties, it is reasonable to believe that a layup design that does can be developed. Since this is considered to be a problem to be addressed in the design phase it has not been addressed here.

The issue of transient temperature conditions cannot be addressed until the material problem is considered further. However, under transient temperature conditions the temperature change of the composite metering tube is greater than that of the aluminum centerpiece. This is advantageous since the radial coefficient of expansion of the metering tube is less than that of the aluminum centerpiece. Therefore the issue of transient temperature loads is not considered to be as important as the material issue.

The wind loading issue is that of not having representative wind loads applied to the structure. This is most important when considering the evaluation of the tube type metering structure. The metering tube has substantial surface area compared to a truss type metering structure. Wind loads on the spiders is an important issue as well.

Although evaluation of wind loads on the metering tube could suggest that a truss type metering structure is better, replacing the upper portion of the metering tube with truss would not change the overall structural concept appreciably.

Wind loading on the entire structure is an issue as well. Because cavity wind loads on the structure could possibly be cyclic in nature, they could induce resonance of the structure if the frequency of the load is near a natural frequency of the structure. However, the lowest natural frequency of the conceptual telescope structure is reasonably high, reducing the possibility of such an occurrence.

## **TELESCOPE STRUCTURE OPEN ISSUES**

- TEMPERATURE STABILITY:
  - IMAGE STABILITY DUE TO TEMPERATURE CHANGE NEEDS FURTHER STUDY
  - TRANSIENT TEMPERATURE LOAD CONDITIONS HAVE NOT BEEN APPLIED TO THE STRUCTURE
- WIND LOADING:
  - REPRESENTATIVE WIND LOADS HAVE NOT BEEN DEVELOPED OR APPLIED TO STRUCTURE

## Primary Mirror Structural Support System - Introduction

This subsection comprises a design description of a mirror support system for the baseline SOFIA ULE square-webbed mirror. The chief design problem is in structurally supporting the mirror in such a fashion that the mirror figure requirements are met. Factors that affect mirror figure distortion are:

- Gravity and changes in the direction of gravity with respect to the mirror axis due to changing elevation angle (20 to 60 degrees)
- Temperature changes and temperature gradients in the mirror support frame
- Dynamic loading of the mirror or its support frame, where the sources of dynamic loading are:
  - Aircraft platform vibration that is transmitted to the mirror structure
  - Air pressure variation (static and dynamic): 1) directly on the mirror or mirror support frame, and 2) on the telescope structure which accelerates and dynamically deforms the telescope and in turn accelerates and dynamically deforms the mirror support frame

It is not practical at this stage of analysis to relate each calculated mirror figure directly to image quality. As a convenience of structural analysis, the following criteria of acceptable distortion have been used for guideline purposes:

- That the root mean square of distortion in the mirror axis direction from the desired figure at points along any curve of constant radius (as illustrated on the upper left-hand sketch in the chart) should be  $\leq 0.21 \mu\text{m}$
- Similarly, that the rms axial distortion along any straight line that bisects the mirror axis (as on the right-hand sketch) should concurrently be  $\leq 0.21 \mu\text{m}$

Guidelines used for maximum time variations of the axial position of the mirror and mirror tilt are  $0.5 \mu\text{m}$  and  $0.05 \text{ arcsec}$ , respectively.

Calculated mirror distortion for various operational conditions is shown on subsequent pages. It should be mentioned that the magnitudes of highly local distortions are subject to some inaccuracy due to the method of modeling, however the errors are not of such magnitude that the general conclusions of this section are misleading. For the calculational result of mirror distortion given below, it was assumed that the mirror was polished to the desired figure with its axis vertical and with its backplate lying against a flat, rigid plate.

### TELESCOPE STRUCTURE OPEN ISSUES

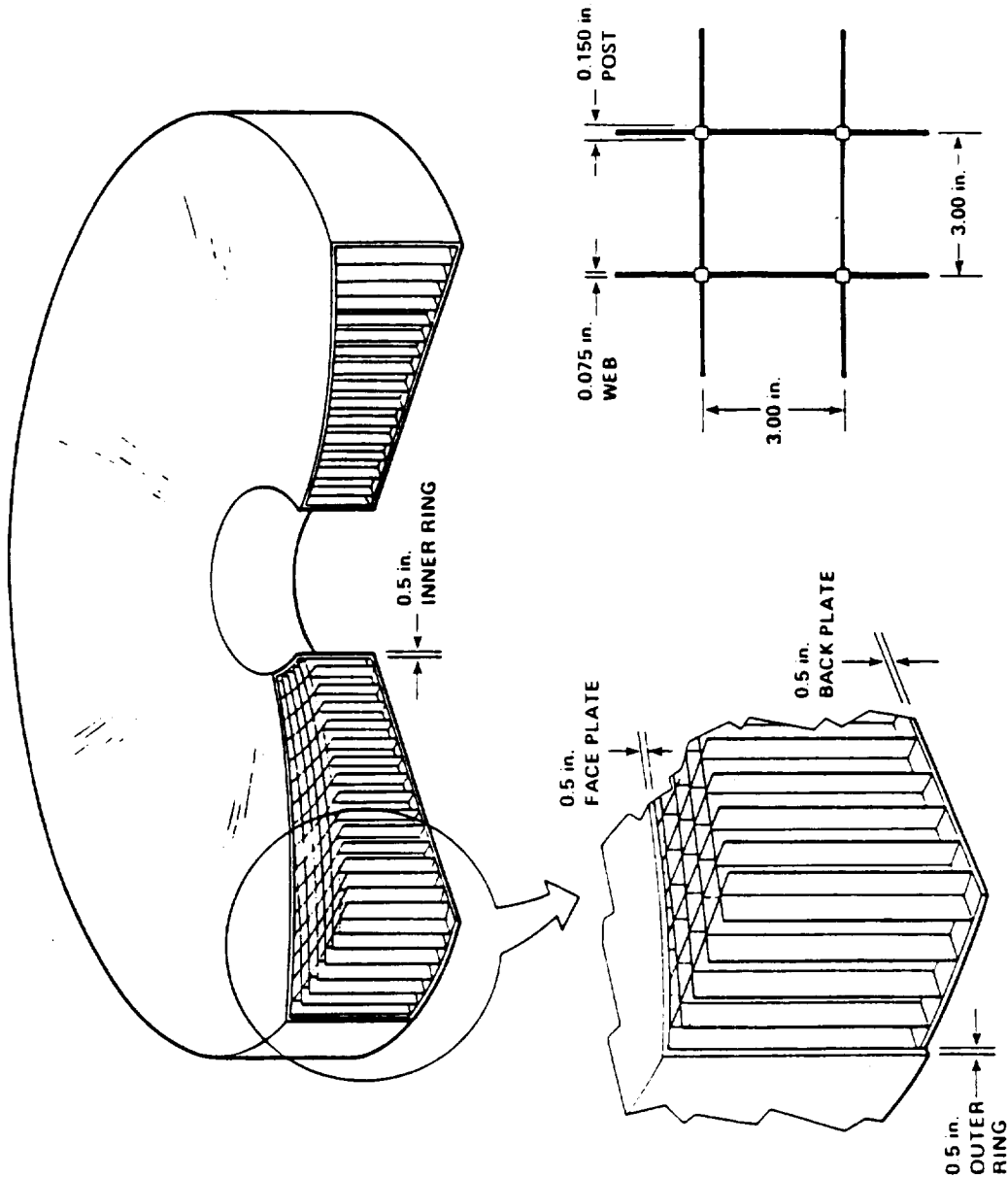
- TEMPERATURE STABILITY:
  - IMAGE STABILITY DUE TO TEMPERATURE CHANGE NEEDS FURTHER STUDY
  - TRANSIENT TEMPERATURE LOAD CONDITIONS HAVE NOT BEEN APPLIED TO THE STRUCTURE
- WIND LOADING:
  - REPRESENTATIVE WIND LOADS HAVE NOT BEEN DEVELOPED OR APPLIED TO STRUCTURE

### Primary Mirror Model

The chart illustrates the dimensions and construction of the "baseline" SOFIA primary mirror, which was used to develop the support system concept. This mirror design is based on an extension of the lightweight, optical quality Hubble Space Telescope primary, and consists of a ULE faceplate, backplate, and outer ring, "frit-bonded" to an inner square web of the same material. More information regarding the primary mirror concept is found in Section 4.1.

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## BASELINE SOFIA PRIMARY MIRROR - 3.0 m DIAMETER SQUARE WEB



### Axial Support of Mirror

The axial support system comprises an array of supports that interface with the backplate of the mirror. At each interface location, a predetermined force is applied by the support member to the contact area of the backplate. At three of the interface points, the support member is rigidly connected (hinged) to the backplate, and the remaining interface areas are in simple compressive contact (i.e., the mirror is resting on the supports). The three-point rigid connection prevents mirror dislodgement under abnormally large aircraft acceleration and also relates to control of dynamic mirror response.

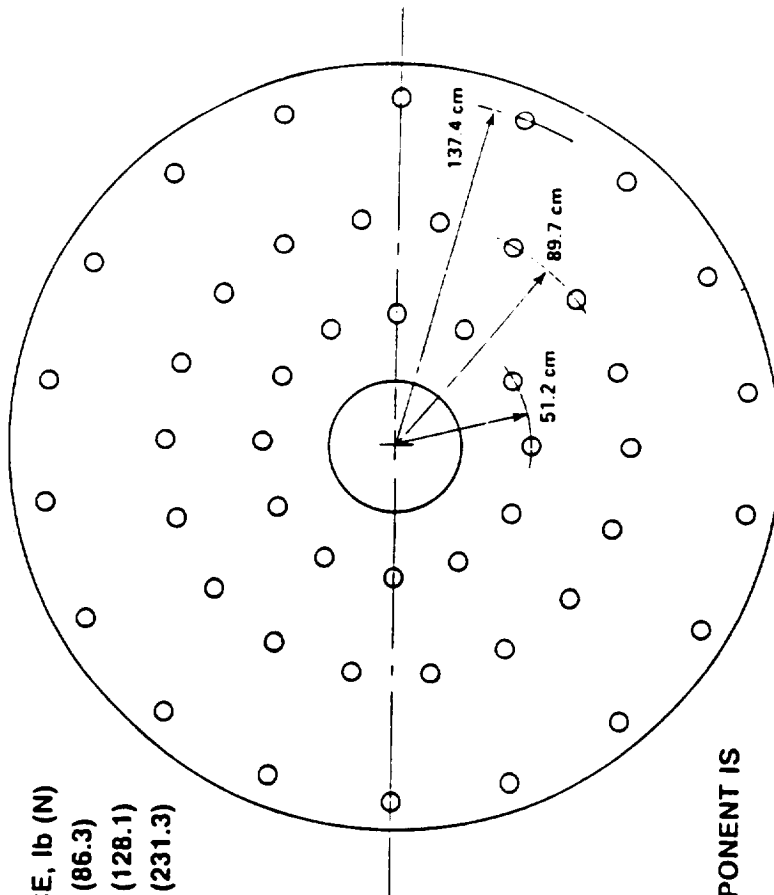
The force is applied at each interface by a pneumatic piston, one piston for each support point (details of the pistons are given later). In general, the required applied force depends on the radial position of the support point, and the applied force also must be varied with the sine of the elevation angle.

Mirror distortion was analytically evaluated for a variety of axial support arrangements. The total number of supports was varied from 9 to 48, and various spatial distributions of support points and various distributions of applied force at the support points were examined. The results given in this section are based on one arrangement only; the distortion from this arrangement was judged to be a suitable fraction of the distortion budget. This system comprises 48 support points as configured on the chart.

### AXIAL SUPPORT ARRANGEMENT

FORCE APPLIED AT SUPPORT POINTS  
FOR ELEVATION ANGLE OF 40 DEGREES

RADIUS, in. (cm)	FORCE, lb (N)
20.2 (51.2)	19.4 (86.3)
35.3 (89.7)	28.8 (128.1)
54.1 (137.4)	52.0 (231.3)



#### LEGEND

- AXIAL SUPPORT LOCATION

NOTE: AXIAL GRAVITY COMPONENT IS  
INTO THE PAGE

#### Mirror Axial Distortion Due to the Axial Component of Gravity

The contours on the opposing page indicate distortion in the mirror axis direction caused by the axial component of gravity. The contours are for the median elevation angle of 40 degrees.

It can be seen from the contours that the mirror departs from the desired figure by no more than 0.090  $\mu\text{m}$ . Footprints from forces applied through each backplate support point are also evident, although the magnitude of the footprint distortions are small compared to global distortion. Global distortion can be reduced by manipulating the spatial and force distributions of the 48 supports, but this tends to increase the magnitude of footprint distortion, and the results given represent a compromise between the two types of distortion.

The axial support configuration has not been optimized with respect to mirror figure (or image quality), although the dependence of distortion on the number and arrangement of support locations has been systematically explored. On the basis of current results, it is thought that an acceptable distortion will not be achievable with significantly fewer than 48 axial supports.

Various calculations of root mean square distortion have been obtained. Calculations of rms distortion from points along circumferential curves (curves of constant radii) indicate a worst case of 0.02  $\mu\text{m}$  (at radii of 115 cm and 129 cm). The largest rms distortion along radial spokes is 0.06  $\mu\text{m}$ , and the rms for the entire mirror is 0.06  $\mu\text{m}$ .

The most severe distortion due to gravity in the axial direction is for the elevation angle of 60 degrees. For this case, the worst circumferential and radial rms distortions are 0.03 and 0.08  $\mu\text{m}$ , respectively. These rms distortions are well below the total budget guidelines given earlier of 0.21  $\mu\text{m}$ .

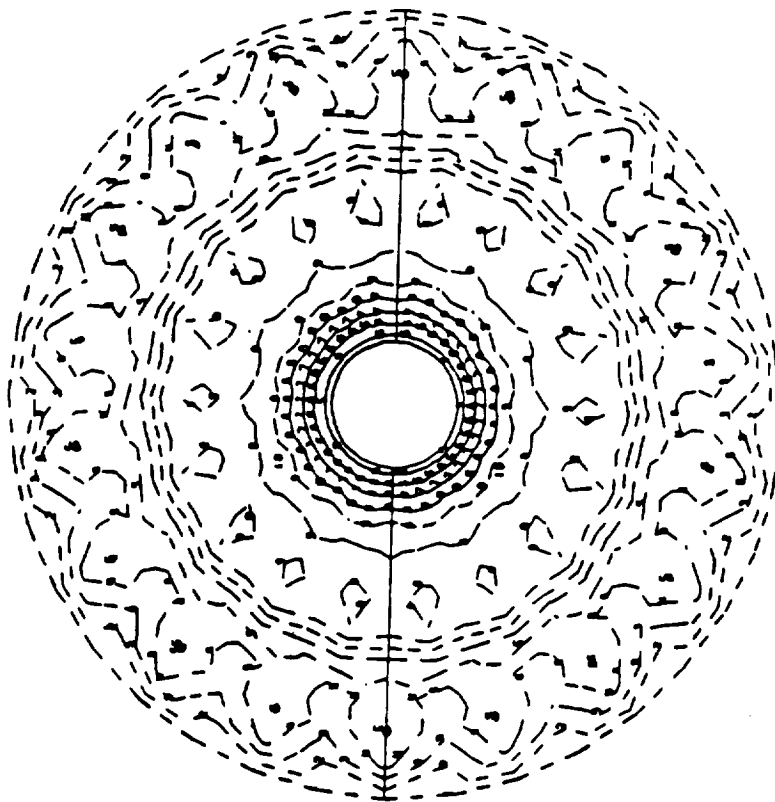
## AXIAL DISTORTION DUE TO AXIAL GRAVITY COMPONENT

CONTOUR # DISTORTION

1 -0.090  $\mu\text{m}$

10 +0.090  $\mu\text{m}$

CONTOUR INTERVAL: 0.018  $\mu\text{m}$



NOTES:

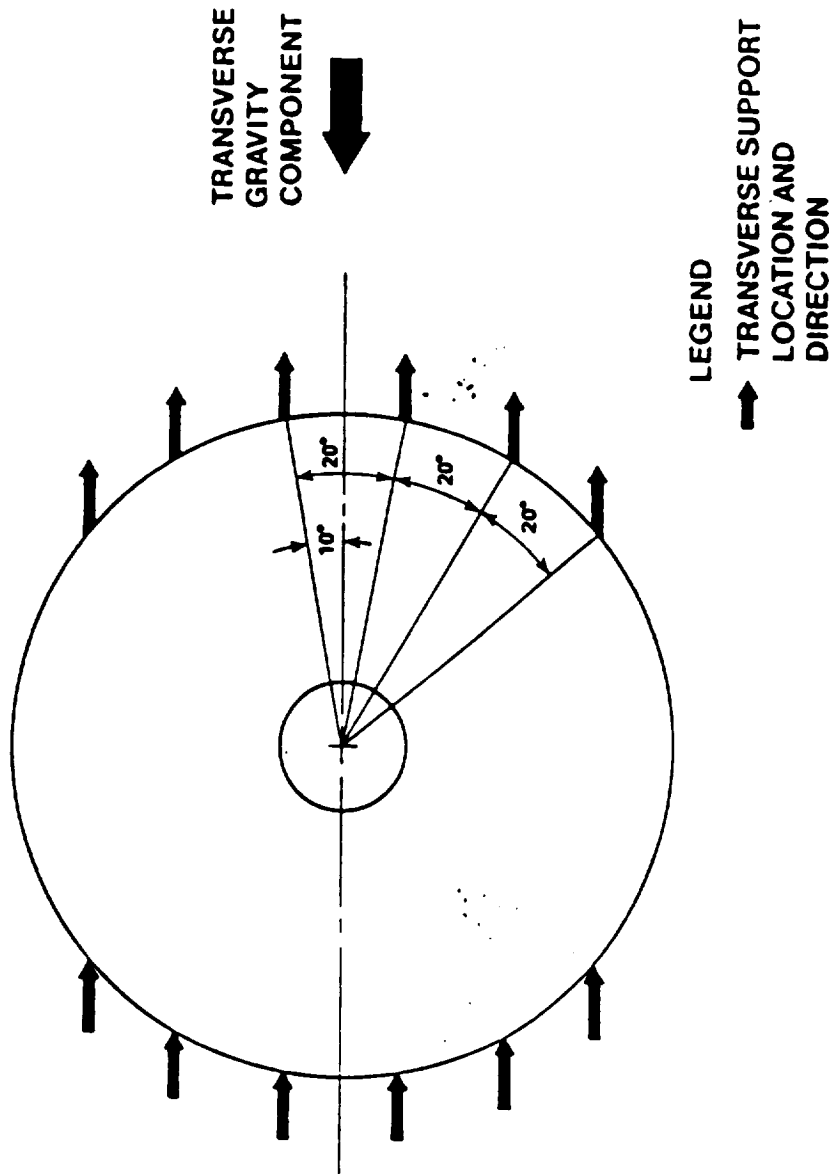
- AXIAL GRAVITY COMPONENT IS INTO THE PAGE.
- MINUS INDICATES DEFLECTION INTO THE PAGE.

### Transverse Support of Mirror

The component of gravity perpendicular to the mirror axis (the transverse component) causes a mirror figure distortion of non-axisymmetric character as well as a transverse displacement of the mirror faceplate with respect to the backplate (a web shearing). For large, webbed mirrors, a transverse support system is used to minimize this distortion and displacement; commonly, transverse support systems are designed to interface with the mirror at numerous locations on the mirror web, typically at the local c.g. between the backplate and faceplate for each location (see references for Apache Point, Kitt Peak). For the baseline SOFIA mirror, various problems were anticipated with web interface designs, primarily because of the comparatively small thickness of the webs (0.075 in). It was thought that an impractically large number of support locations with large contact areas would be required, and that this in turn could lead to substantial problems of alignment. Consequently, a design concept wherein the mirror is supported along the comparatively stiff outer peripheral ring was explored, and a successful support system of this design was developed.

An illustration of the transverse support configuration which provided the best overall result to date is given on the opposite page. The system comprises twelve support locations which are distributed at 20 degree-of-arc intervals along the upper and lower perimeter. The direction of the forces applied to the mirror at these contact points is opposite to the component of gravity in the plane of the mirror, and the contact points are located in the c.g. plane of the mirror. The mirror distortion was found to be minimum when the magnitudes of the applied force at each contact point were equal or near equal. Similar to the axial supports, the applied force must be varied with elevation angle, in this case with the cosine of the angle. For an elevation angle of 40 degrees, for example, the magnitude per transverse support point is 107 lbs.

## TRANSVERSE SUPPORT ARRANGEMENT



### Mirror Axial Distortion due to Transverse Component of Gravity

Contours given on the opposite page indicate mirror distortion in the axial direction due to the component of gravity in the transverse direction. The contours are for the median elevation angle of 40 degrees.

A prominent characteristic of the contours is that the most significant distortion occurs near the mirror edge adjacent to the supports, and that the distortions shown on the right side are identical but of opposite sign (direction) to those on the left. At a glance, the worst rms distortion appears to be along a circumferential curve at or near the edge of the mirror, and proves to be 0.14  $\mu\text{m}$  rms at the edge ( $r = 150\text{ cm}$ ). While this is within the guideline budget of 0.21  $\mu\text{m}$  rms, distortion due to transverse loads represent a sizeable fraction of the budget (0.62).

The elevation angle that produces the largest distortion is 20 degrees. A table showing worst case rms distortions for the elevation angles of 20 and 40 degrees is given below.

**Worst Case RMS Axial Distortion (in  $\mu\text{m}$ ) due to Transverse Gravity Loads**

<u>Elevation Angle, deg.</u>	<u>Circumferential</u>	<u>Radial</u>	<u>Entire Mirror</u>
20	0.17	0.09	0.08
40	0.14	0.08	0.07

## AXIAL DISTORTION DUE TO TRANSVERSE GRAVITY COMPONENT

CONTOUR # DISTORTION

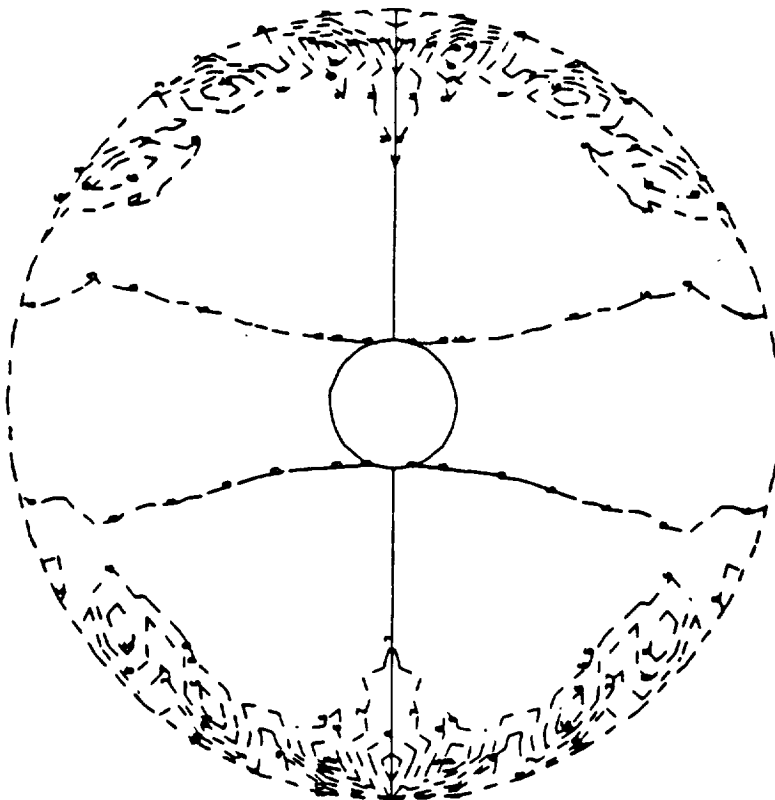
1 -0.254  $\mu\text{m}$

10 +0.254  $\mu\text{m}$

CONTOUR INTERVAL: 0.051  $\mu\text{m}$



TRANSVERSE  
GRAVITY  
COMPONENT



NOTE: MINUS INDICATES DEFLECTION  
INTO THE PAGE.

**Mirror Axial Distortion due to the Combined Effect of Axial and Transverse Gravity Components**

The contours on the opposing page indicate distortion in the mirror axis direction due to the combined effect of axial and transverse components of gravity. The contours are for the median elevation angle of 40 degrees.

It is evident that the transverse component of gravity dominates the overall distortion. Less effort was expended towards optimizing the transverse support system, and it is thought that substantial improvements can be achieved without unduly complicating the transverse system.

The table below indicates the worst case rms distortions at the three elevation angles of 20, 40 and 60 degrees. It can be seen from the table that the largest rms distortions in the circumferential and radial directions are 0.17  $\mu\text{m}$  and 0.10  $\mu\text{m}$ , respectively, both below the 0.21  $\mu\text{m}$  guideline budget.

Worst Case RMS Distortion (in $\mu\text{m}$ ) due to Gravity Loads			
Elevation Angle, deg	Circumferential	Radial	Entire Mirror
20	0.17	0.10	0.09
40	0.14	0.10	0.09
60	0.09	0.10	0.09

CONTOUR # DISTORTION

1 -0.279  $\mu\text{m}$

**10** **+0.279  $\mu\text{m}$**

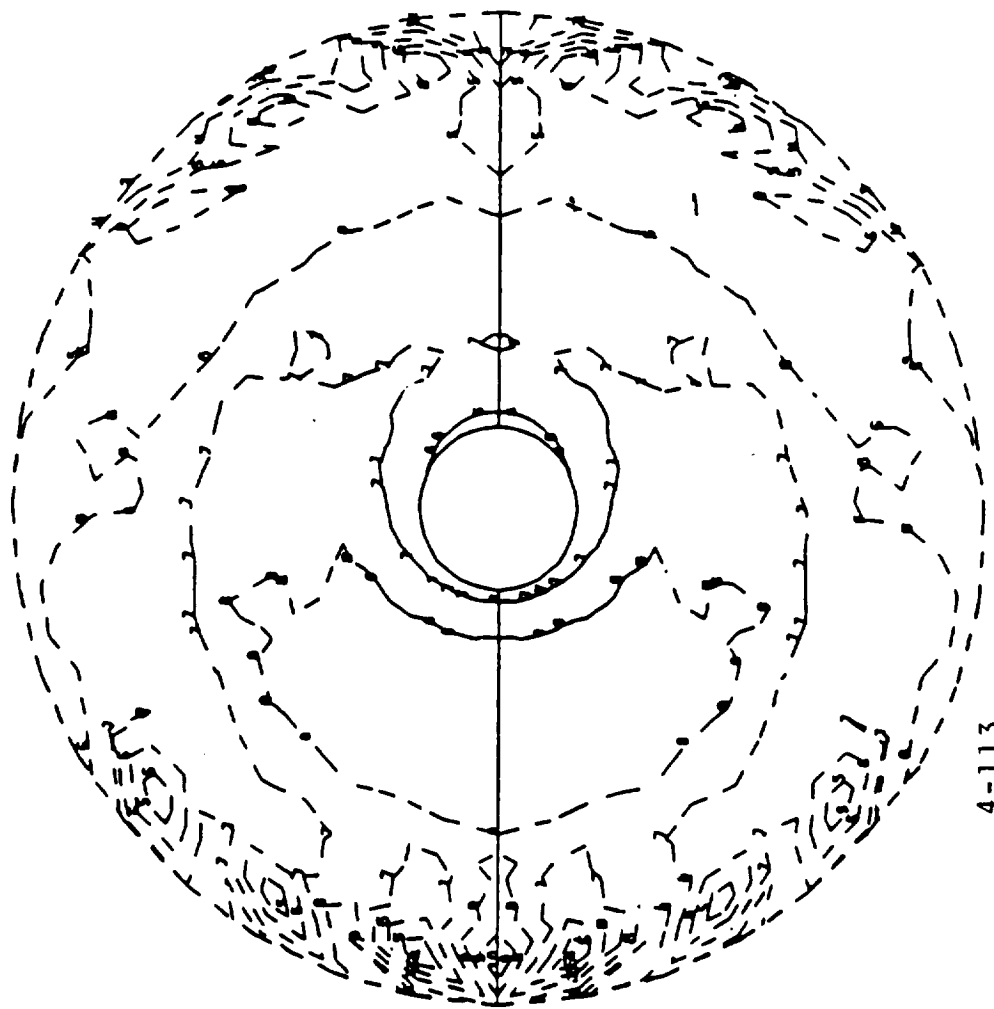
**CONTOUR INTERVAL: 0.056  $\mu\text{m}$**



**TRANSVERSE  
GRAVITY  
COMPONENT**

**NOTES:**

- AXIAL GRAVITY COMPONENT IS INTO THE PAGE.
- MINUS INDICATES DEFLECTION INTO THE PAGE.



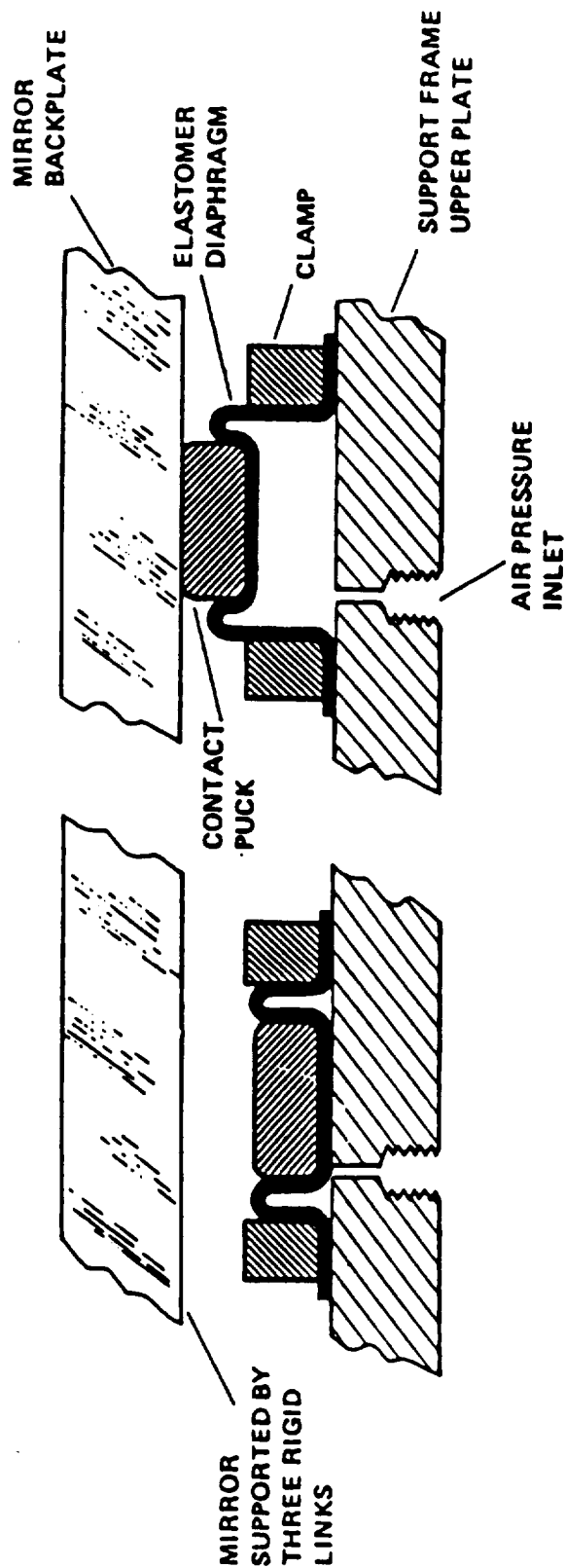
### Pneumatic Linkage Between Mirror and Support Frame

Mirror support forces, as mentioned above, are applied to the mirror through a system of pneumatic pistons, one piston for each support point. There are several advantages of the pneumatic system over earlier mechanical linkage methods, and in recent years pneumatic-based mirror supports have been used for a number of telescopes (Apache Point 3.5 meter, NOAO 4 meter, Herschel 4.2 meter, etc.). For SOFIA, the primary advantages of pneumatic support are that:

- The mirror figure is relatively insensitive to
  - Thermal warpage of the support frame
  - Thermally induced differential displacements between the mirror and support frame
  - Deformation (bending) of the support frame due to gravity load changes (elevation angle changes)
- High precision positioning of the mirror to support frame linkage is not required
- Required support force variations with elevation angle are readily controlled

An illustration of the pneumatic piston in operational (pressurized) position and collapsed (unpressurized) position is shown on the opposing page. Piston displacement is accompanied by a bending (rolling) of the elastomer diaphragm, and the displacement is nearly friction free. Ideally, the force acting on the mirror would be independent of piston position so that the load applied to the mirror would not be affected by deformations of the support frame. In reality, there is a slight variation of force with piston position, and this dependence has been evaluated through tests conducted at the University of Washington using commercially available diaphragms (reference 1). On the basis of this evaluation, and on the basis of support frame deformations caused by gravity load and temperature variations (details given in next section), mirror force variations are estimated to be no larger than about 1/4 lb.

## CROSS-SECTION OF PNEUMATIC PISTON\*



COLLAPSED (UNPRESSURIZED) POSITION

OPERATIONAL (PRESSURIZED) POSITION

\* SKETCH TAKEN FROM "DESIGN OF THE APACHE POINT OBSERVATORY 3.5m TELESCOPE III - PRIMARY MIRROR SUPPORT SYSTEM," E.J. MANNERY, W.A. SIEGMUND, AND M.T. HULL, ASTRONOMY DEPT., U. WASHINGTON, SEATTLE, WA, MARCH 1987.

#### Pneumatic Linkage (Contd)

An illustration of mirror figure distortion caused by a force error of 1/4 lb. at two support points is shown on the chart. It can be seen that the error creates a "hill" on the mirror surface whose height is about 0.04  $\mu\text{m}$ , well under limits of concern.

The piston also imparts an undesirable transverse force on the mirror when it is displaced in the transverse direction. In this case, the thermally induced differential displacement between the mirror and support frame is the dominant adverse factor, and conservative estimates of the maximum transverse force is 6 lb. Mirror distortion caused by this force has not yet been evaluated for the square-webbed mirror; for forces of similar magnitude, analysis conducted at the University of Washington (reference 1) showed the distortion to be insignificant for the Apache Point hex-core mirror.

It is important for the elastomeric diaphragm (shown on the sketch of the pneumatic piston) to maintain a high flexibility in bending. For previous mirror support applications, the diaphragms have been made of materials such as neoprene that are reinforced with a thin, embedded fabric. The low operating temperatures for SOPA may require one of the low temperature elastomers whose applicability for these supports has not been established. It is recommended that suitable diaphragm materials be studied for fabricability and for flexibility and endurance at operational temperatures to insure that the required flexibility and a practical diaphragm life can be achieved.

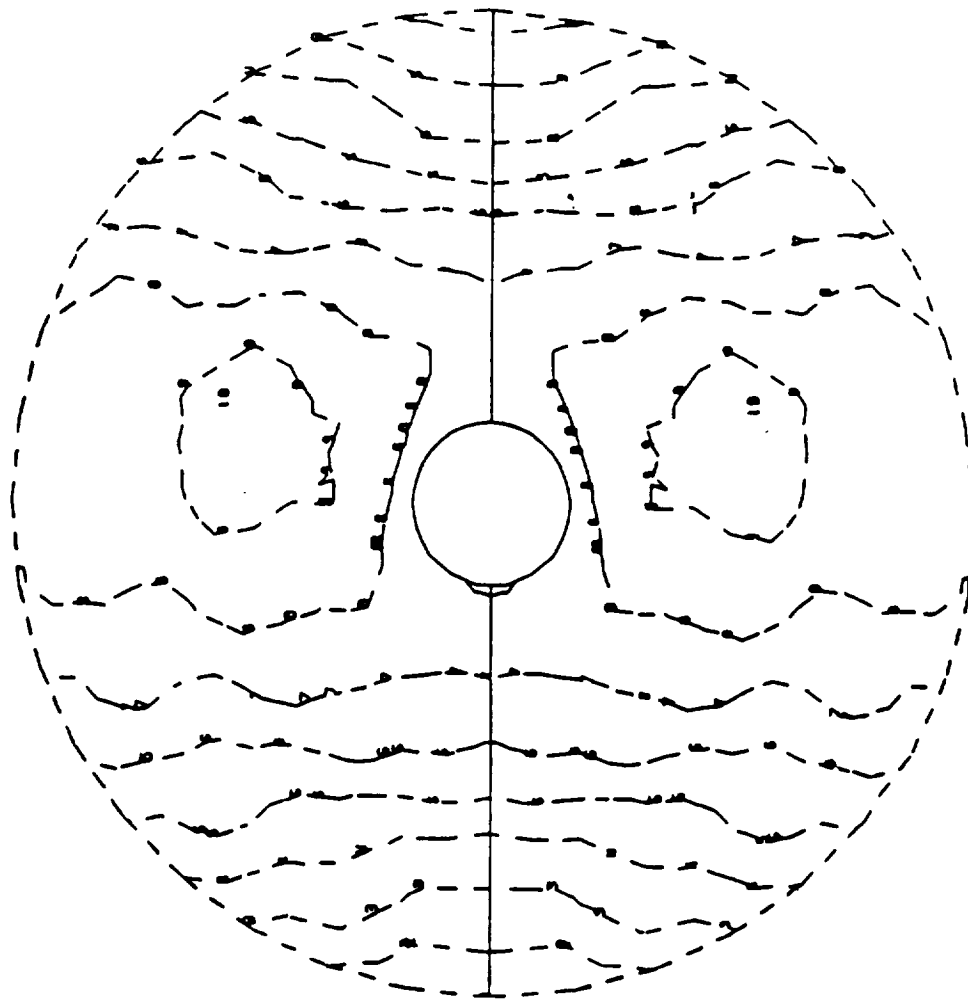
## AXIAL DISTORTION DUE TO LOCAL FORCE ERROR

CONTOUR # DISTORTION

1 -0.000  $\mu\text{m}$

10 +0.090  $\mu\text{m}$

CONTOUR INTERVAL: 0.009  $\mu\text{m}$



NOTES:

- AXIAL GRAVITY COMPONENT IS INTO THE PAGE.
- MINUS INDICATES DEFLECTION INTO THE PAGE.

### Primary Mirror Support Frame

As described on the previous page, deformation of the support frame, or differential displacement between the support frame and mirror, will cause an error in the force applied to the mirror by the pneumatic piston. The support frame was designed to minimize these effects, but constraints on weight, volume (geometric envelope) and cost were also considered.

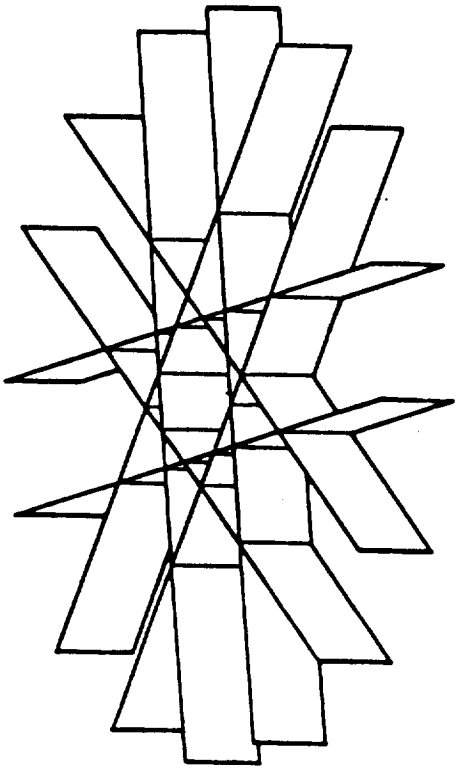
The support frame consists of an upper and lower plate joined by a web structure, where the web is configured as illustrated on the opposing page. The baseline support frame is constructed of graphite/epoxy composite, although an aluminum frame of identical configuration was analyzed in the interest of cost consideration. Various factors of the baseline and aluminum frames are listed in the table below. While an aluminum frame would be comparatively inexpensive, it can be seen from the table that the weight penalty with aluminum is significant, and it is possible that displacement of 0.8 mm (column 5) may preclude an aluminum frame.

### Support Frame Characteristics - Graphite/Epoxy vs. Aluminum

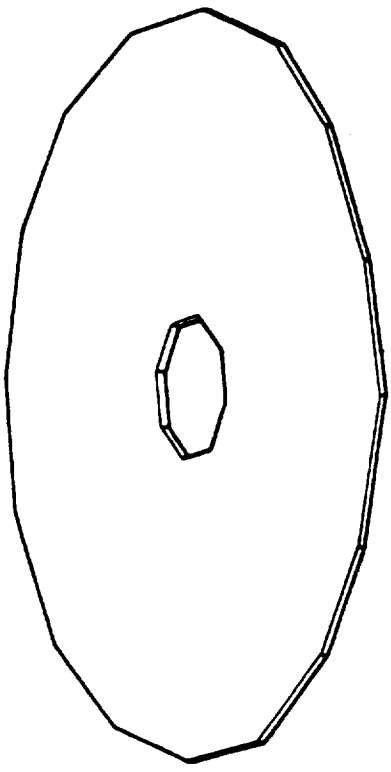
<u>Material</u>	<u>Mass, lb(kg)</u>	<u>Thickness Axial Direction) cm (in)</u>	<u>Max. Bending Deflection over Eleva- tion Angle Range, <math>\mu</math>m</u>	<u>Max. Transverse Differential Displacement of Frame with respect to Mirror, mm</u>	<u>Fundamental Resonance in Bending, Hz</u>
Graphite/ Epoxy (Baseline)	2646(1200)	44.5(17.5)	3	0.15-0.30	104
Aluminum	4519(2050)	44.5(17.5)	3	0.80	-

## WEB STRUCTURE OF MIRROR SUPPORT FRAME (UPPER PLATE NOT SHOWN)

MATERIAL FOR BASELINE — GRAPHITE/EPOXY



WEB STRUCTURE  
THICKNESS = 0.25 in.  
HEIGHT = 16.5 in.



LOWER PLATE  
THICKNESS = 0.5 in.

### Dynamic Distortion and Dynamic Displacement of Primary Mirror

Vibrations of the aircraft platform are transmitted through the structure to the primary mirror causing 1) a vibratory distortion of the mirror figure, 2) an oscillation of the focal point (vibration of the axial position of the primary mirror with respect to the secondary mirror) and 3) a vibratory tilting of the primary. Estimates have been made of the maximum amplitudes of primary mirror translation along the telescope axis and mirror surface distortion.

A NASTRAN analysis has predicted resonances of the telescope at various frequencies and an amplitude magnification between the air bearing and primary mirror has been shown. Vertical resonant vibration of the telescope structure at 25 Hz resulted in a translation of the primary mirror 0.3 nm along the axis of the telescope, where the translational limit is 5  $\mu\text{m}$ . Mirror surface distortion was 5.2 nm and more than an order of magnitude less than the 0.21  $\mu\text{m}$  rms primary mirror distortion budget. The principal resonant response at 104 Hz was a 2.1 nm translation of the primary mirror with respect to the secondary mirror due to bending of the primary mirror support frame; again, this is well under the 5  $\mu\text{m}$  limit. Mirror distortion was 2.4 nm and almost two orders of magnitude below its budget. Vibratory resonance at 311 Hz was characterized by bending of the primary mirror which caused a 0.005 nm surface distortion and a 0.001 nm despace.

While a more detailed analysis with improved modeling is still to be performed, preliminary estimates suggest that dynamic distortion effects are small. Transverse displacements appear to be of the same order of magnitude as the above mentioned axial displacements, although more investigation into mounting techniques is necessary. Wind induced dynamic distortions have not been analyzed. Telescope cavity air flow will contribute to primary mirror distortions, and while preliminary estimates indicate that its effect will be small, a further examination is warranted.

### Primary Mirror Stress

Stress in the primary mirror was evaluated by considering a typical mirror web box section and subjecting it to a shear load due to gravity in the plane of the mirror. Based upon an allowable stress for the ULE glass of 1800 psi, stress values in the mirror web were estimated to be less than 1/4 of the allowable under normal operating conditions. Because of this sufficiently small margin, more accurate stress values should be established through high fidelity modeling of the mirror.

Mirror stress estimates considered only normal (i.e., tracking) operating conditions. It is assumed that a caging mechanism will operate under gust and other abnormal acceleration conditions to prevent failure in the mirror. Mirror survival is not expected in the event of a maximum forward crash load of 9 g's though stress should be accurately evaluated for all credible levels of airframe acceleration.

### CONCLUSIONS: PRIMARY MIRROR SUPPORT SYSTEM

- PRELIMINARY ANALYSIS SHOWS THAT MIRROR FIGURE GUIDELINES WITH RESPECT TO GRAVITY INDUCED DISTORTION CAN BE MET WITH A MIRROR SUPPORT SYSTEM COMPRISING 48 AXIAL SUPPORTS AND 12 TRANSVERSE SUPPORTS, WHERE THE TRANSVERSE SUPPORTS ARE LOCATED ALONG THE OUTER PERIMETER OF THE MIRROR. IT IS THOUGHT THAT THE GUIDELINES CANNOT BE MET WITH SIGNIFICANTLY FEWER THAN 48 AXIAL SUPPORT POINTS.
- IT HAS BEEN SHOWN THAT EXISTING PNEUMATICALLY-BASED MIRROR-TO-SUPPORT FRAME INTERFACE TECHNIQUES ARE CAPABLE OF MAINTAINING MIRROR SUPPORT LOADS WITHIN A TOLERANCE THAT SATISFIES MIRROR FIGURE REQUIREMENTS:
  - FOR SUPPORT FRAME DEFORMATION (BENDING) CHANGES THAT OCCUR OVER THE ELEVATION ANGLE RANGE (THIS APPLIES TO EITHER THE BASELINE GRAPHITE/EPOXY SUPPORT FRAME OR AN ALUMINUM SUPPORT FRAME)
  - FOR THERMALLY INDUCED DISTORTION THAT WILL OCCUR IN THE BASELINE SUPPORT FRAME
- WITH THE QUALIFICATIONS THAT:
  - MIRROR DISTORTION CAUSED BY THERMALLY INDUCED DIFFERENTIAL DISPLACEMENTS BETWEEN THE BASELINE SUPPORT FRAME AND MIRROR IN THE TRANSVERSE DIRECTION HAVE NOT BEEN ANALYZED FOR THE BASELINE MIRROR, BUT HAVE BEEN SHOWN TO BE NEGLIGIBLE FOR SIMILAR MIRRORS. (THERE IS SOME DOUBT WHETHER MIRROR FIGURE COULD BE MAINTAINED WITH AN ALUMINUM SUPPORT FRAME.)
  - THERE IS SOME CONCERN WHETHER COMMERCIALLY AVAILABLE DIAPHRAGMS PROVEN FOR MIRROR SUPPORT APPLICATION WILL HAVE ADEQUATE LIFETIME AND WILL MAINTAIN SUITABLE FLEXIBILITY AT SOFIA OPERATIONAL TEMPERATURES.
- ESTIMATES SHOW THAT TRANSMISSION OF AIRCRAFT PLATFORM VIBRATIONS TO THE MIRROR CAUSE:
  - DYNAMIC DISTORTIONS OF THE MIRROR FIGURE THAT ARE SMALL COMPARED TO DISTORTION LIMIT GUIDELINES
  - MIRROR DISPLACEMENT OSCILLATIONS ALONG THE TELESCOPE AXIS WITH AMPLITUDES WELL BELOW THE OPTICAL BUDGET OF  $5\text{ }\mu\text{m}$
  - MIRROR TILT OSCILLATIONS (NOT YET EVALUATED)
- STRESS IN THE PRIMARY MIRROR WEB HAS BEEN ESTIMATED AT APPROXIMATELY 1/4 OF THE ALLOWABLE ULE STRESS UNDER NORMAL OPERATING CONDITIONS
  - MORE DETAILED STRESS ANALYSES SHOULD BE PERFORMED TO MORE ACCURATELY ESTABLISH STRESS LEVELS AT ALL EXPECTED OPERATING CONDITIONS

#### 4.3

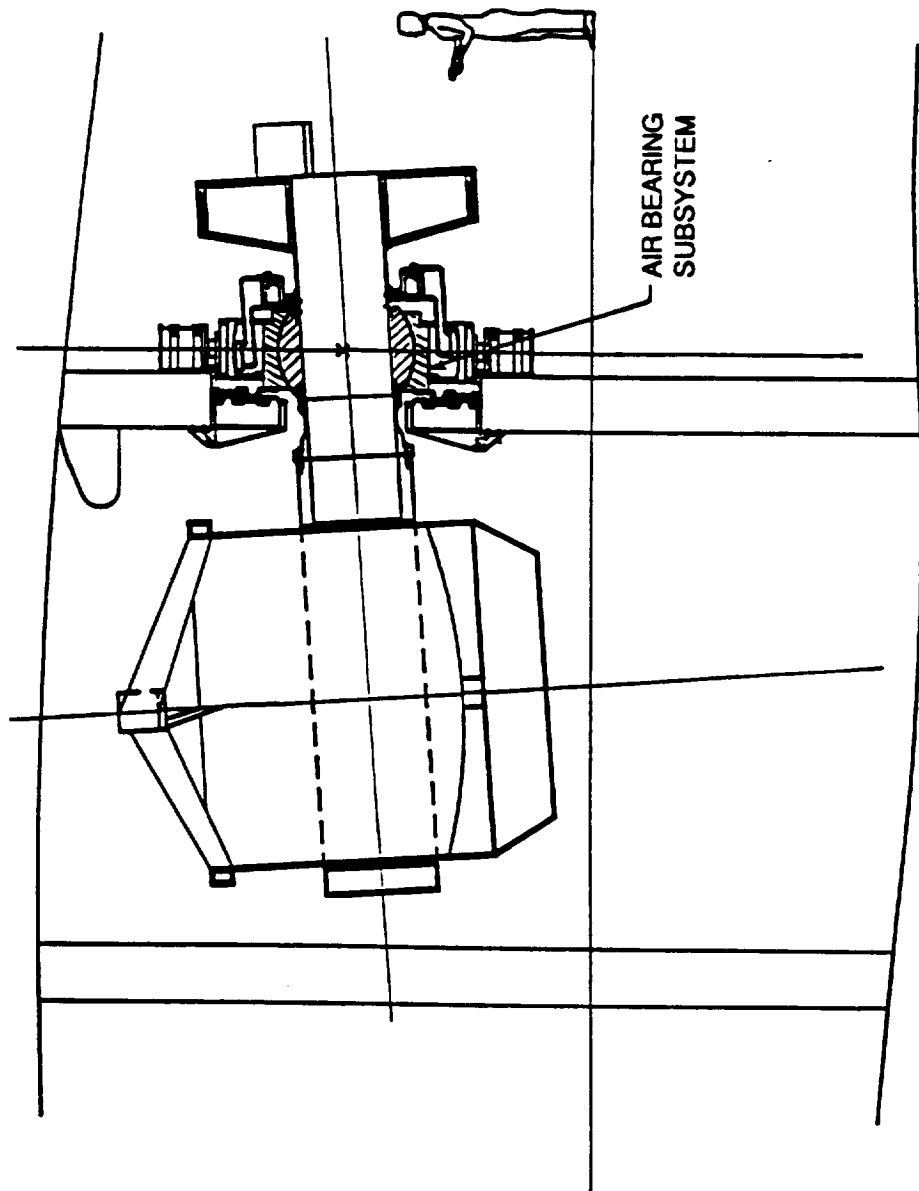
### SOFIA Air Bearing and Vibration Isolation System

#### Air Bearing

##### Scope

The SOFIA air bearing is a spherical ball located at the C.G. of the telescope system. Its purpose is to isolate the three rotational degrees of freedom of the telescope system from the aircraft. The air bearing is mounted in the aft cavity bulkhead wall between the pressurized cabin and the unpressurized cavity. As a result, the bearing is loaded radially due to the weight of the telescope system, and axially due to the pressure difference across the cavity wall. The bearing must also provide interfaces for the telescope centerpiece structure and for the instrument flange structure as both of these structures are attached to the bearing rotor.

## SOFIA AIR BEARING



## **Requirements**

The major requirements for the SOPA air bearing are summarized in the accompanying bullet chart. The four requirements which essentially drive the design are: 1) the 9 psi pressure differential across the bulkhead wall (and hence across the bearing) 2) the desire to have a 31.0 in. diameter hole through the bearing for the optical path 3) the need to maximize the bending stiffness of the ball and 4) providing the interface for the telescope structure and the instrument flange structure.

The latter three requirements are all related to each other in the sense that they all affect the choice of the bearing outside diameter. Reacting the load imposed by the 9 psi pressure differential across the bearing determines the width of the bearing and largely determines the air supply pressure. Therefore, satisfying the above four requirements establishes the bearing geometry and the air supply pressure. All other bearing parameters are calculated based upon the bearing geometry and air supply pressure.

### **SOFIA AIR BEARING REQUIREMENTS**

- TELESCOPE SYSTEM WEIGHT = 20,000 LBS
- 9.0 PSI PRESSURE DIFFERENTIAL ACROSS BULKHEAD WALL
- 135°F TEMPERATURE GRADIENT ACROSS THE BULKHEAD WALL
- + AND - 4 DEGREES MOTION IN L.O.S. AND AZIMUTH (REQUIREMENT UNDER REVIEW)
- PROVIDE 31.0 IN DIAMETER HOLE FOR OPTICAL PATH
- PROVIDE INTERFACE FOR TELESCOPE STRUCTURE AND INSTRUMENT FLANGE STRUCTURE ON BALL
- PROVIDE SEAL OR AIR SCAVENGING SYSTEM TO MINIMIZE AIR LEAKAGE INTO THE CAVITY
- MAXIMIZE BENDING STIFFNESS OF THE BALL
- MINIMIZE THE OVERALL WEIGHT OF THE DESIGN (BALL AND STATOR)
- DETERMINE PRELIMINARY REQUIREMENTS FOR THE AIR SUPPLY
- DESIGN FOR AIRCRAFT CRASH LOADS

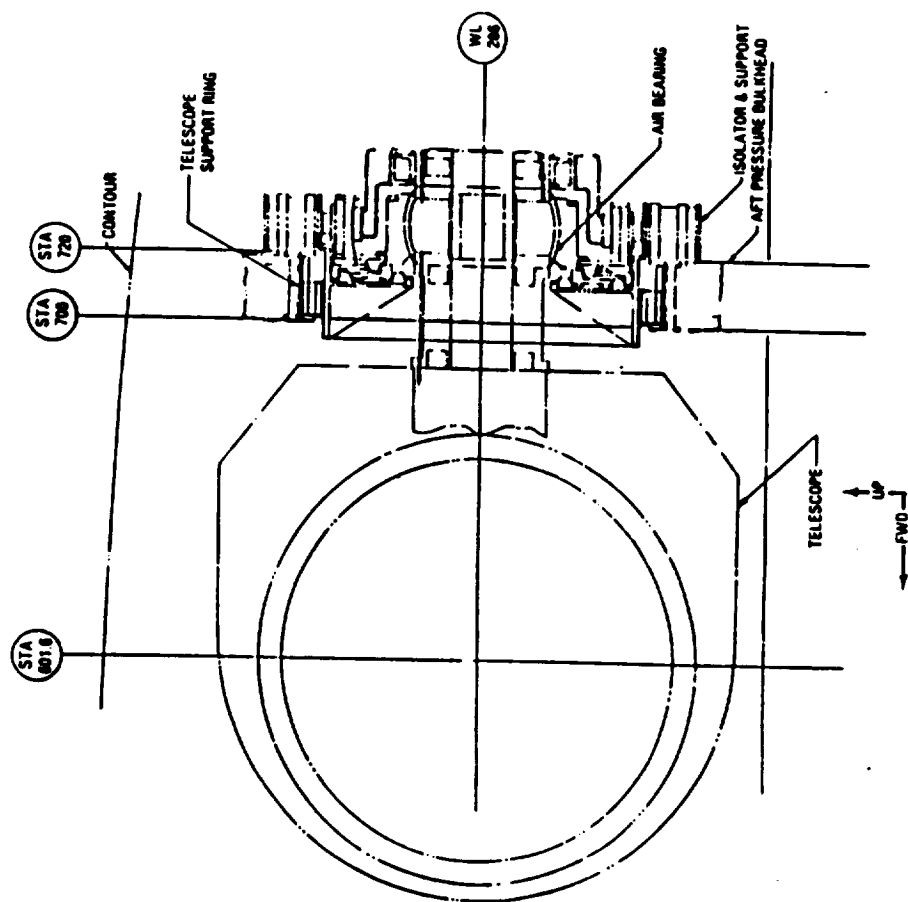
### Design Approach

The SOFIA air bearing is essentially a scaled up version of the KAO air bearing. It consists of a truncated spherical ball (the rotor) which floats on an air film in a truncated spherical seat (stator). This design is preferable over other designs (e.g., gimbal) for reasons of compactness of design, isolation of all three rotational degrees of freedom from the aircraft, and for simplicity of control since all three axes of rotation remain orthogonal to each other.

The spherical design provides for unlimited rotation in the elevation direction (i.e., rotation in elevation is not limited by the bearing). The truncation of the ball limits the rotation in the L.O.S. and azimuth directions but the rotation is adequate to satisfy the design requirements. This truncation also establishes flat surfaces on either side of the bearing for the attachment of the telescope structure and the instrumentation flange.

The use of air as a working fluid is desirable because it is easy to collect and is readily obtainable. Using a fluid such as oil would prove difficult to seal and leakage, with subsequent contamination of the optics, would always be a possibility.

### SOFIA AIR BEARING



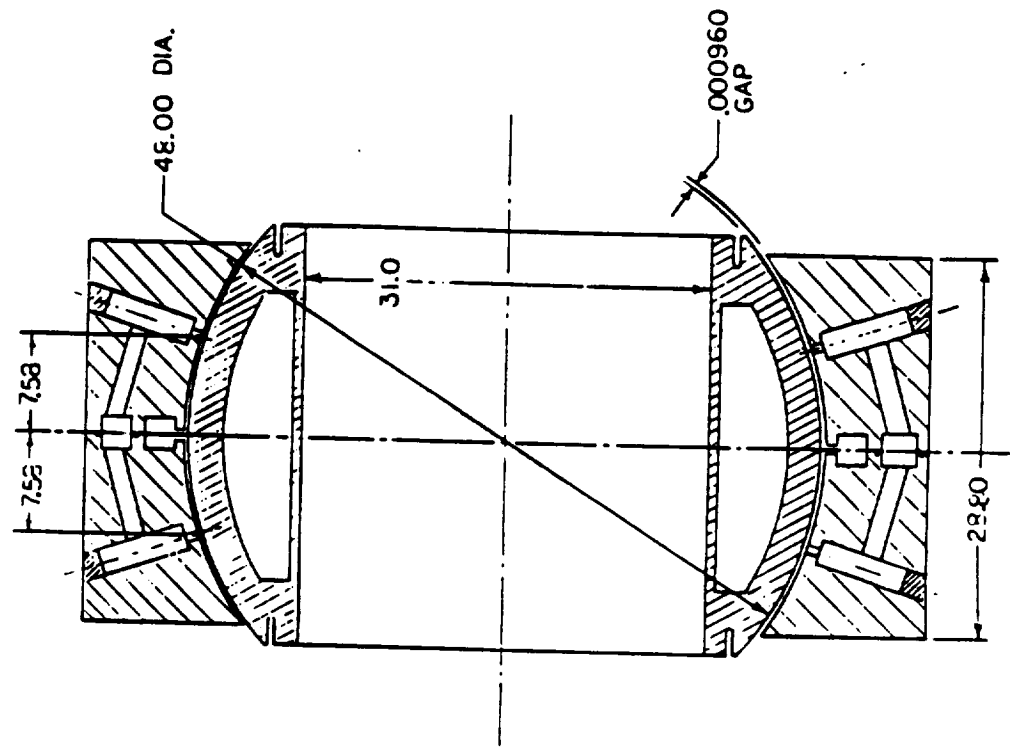
### Concept Details

The major design features of the SOFIA air bearing are shown in the accompanying figure.

The bearing is a truncated sphere providing two flat surfaces for the attachment of the telescope structure and the instrumentation flange. The sphere allows for + and - 4 degrees of rotation in the azimuth and LOS directions and unlimited rotation in the elevation direction. There is a 31 in. diameter bore through the ball for the optical path.

Air is introduced into the gap through two rows of forty feed holes, one row in each half of the bearing. The feed holes are supplied with air from a manifold built into the bearing seat. Inherent restrictors are used to reduce the possibility of pneumatic hammer instability as well as for ease of manufacture. The air exhausts at each end of the bearing seat as well as through an exhaust manifold built into the center of the bearing seat.

## SOFIA AIR BEARING



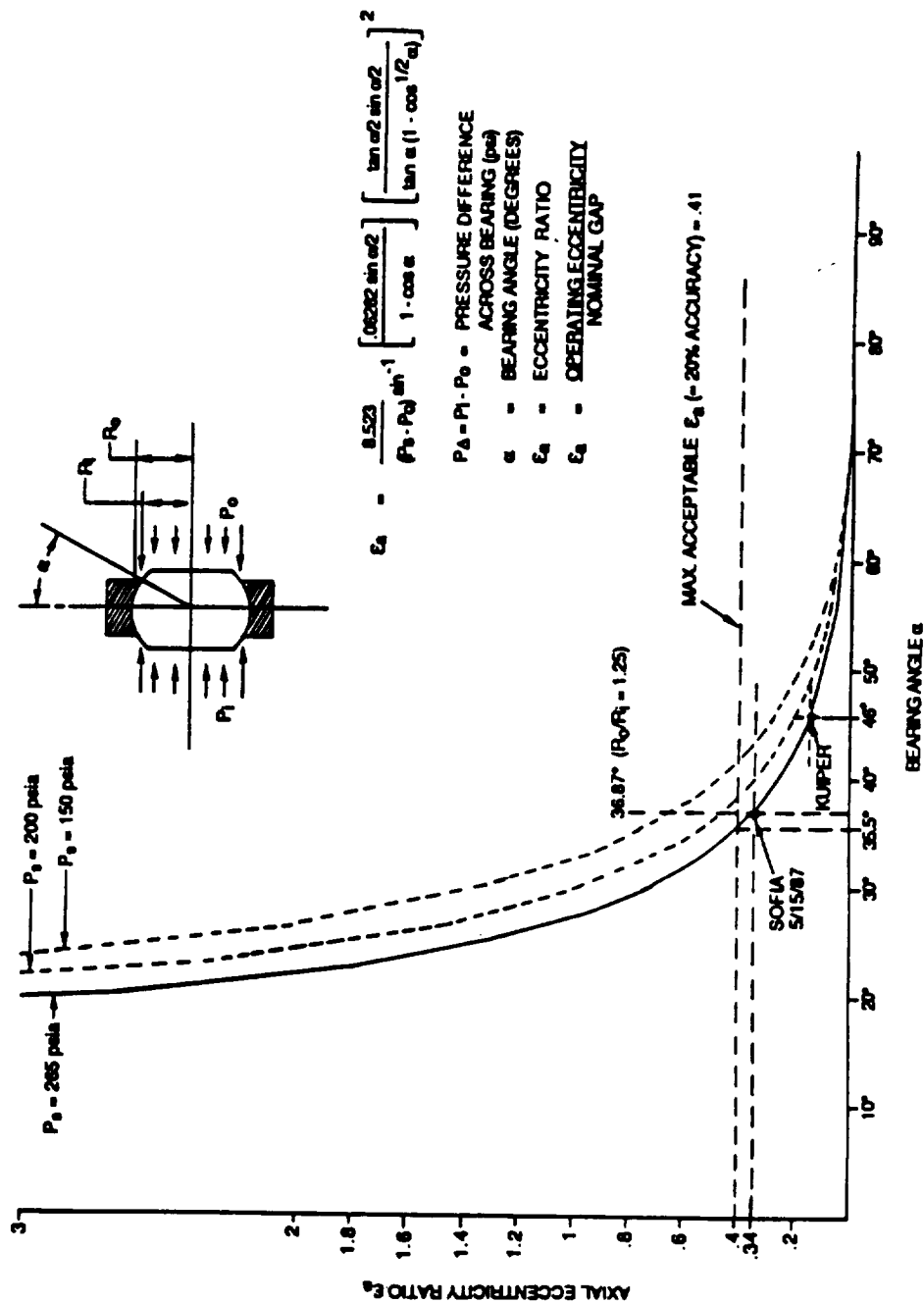
### Concept Details (Cont'd)

The outside diameter of the bearing needs to be a certain minimum size for several reasons: 1) to maximize the bending stiffness of the ball; 2) to provide a 31 in. diameter hole for the optical path; and 3) to provide flat surfaces (for attaching the telescope structure and the instrument flange) of sufficient size that these connections are adequately stiff in bending. Based on these requirements, a 48.0 in. diameter ball was chosen.

The 9 psi pressure load puts a 10423 lb. axial load on the bearing. The ability of the bearing to react this load is governed by two factors: 1) air supply pressure; and 2) bearing 'wrap' angle (see the accompanying figure). The higher the air supply pressure, the less the bearing needs to 'wrap' and, as a result, the bearing will weigh less. An air supply pressure of 265 psi was chosen because this is one of the highest pressures for which design data was available and it is the lowest pressure that would allow a 31.0 in. diameter hole through the bearing yet still react the load with an acceptable operating eccentricity ratio (see the accompanying figure).

It is interesting to note on the figure that the KAO air bearing (which also operates at 265 psi) has an eccentricity ratio of only .12.

### AXIAL ECCENTRICITY RATIO VS BEARING ANGLE



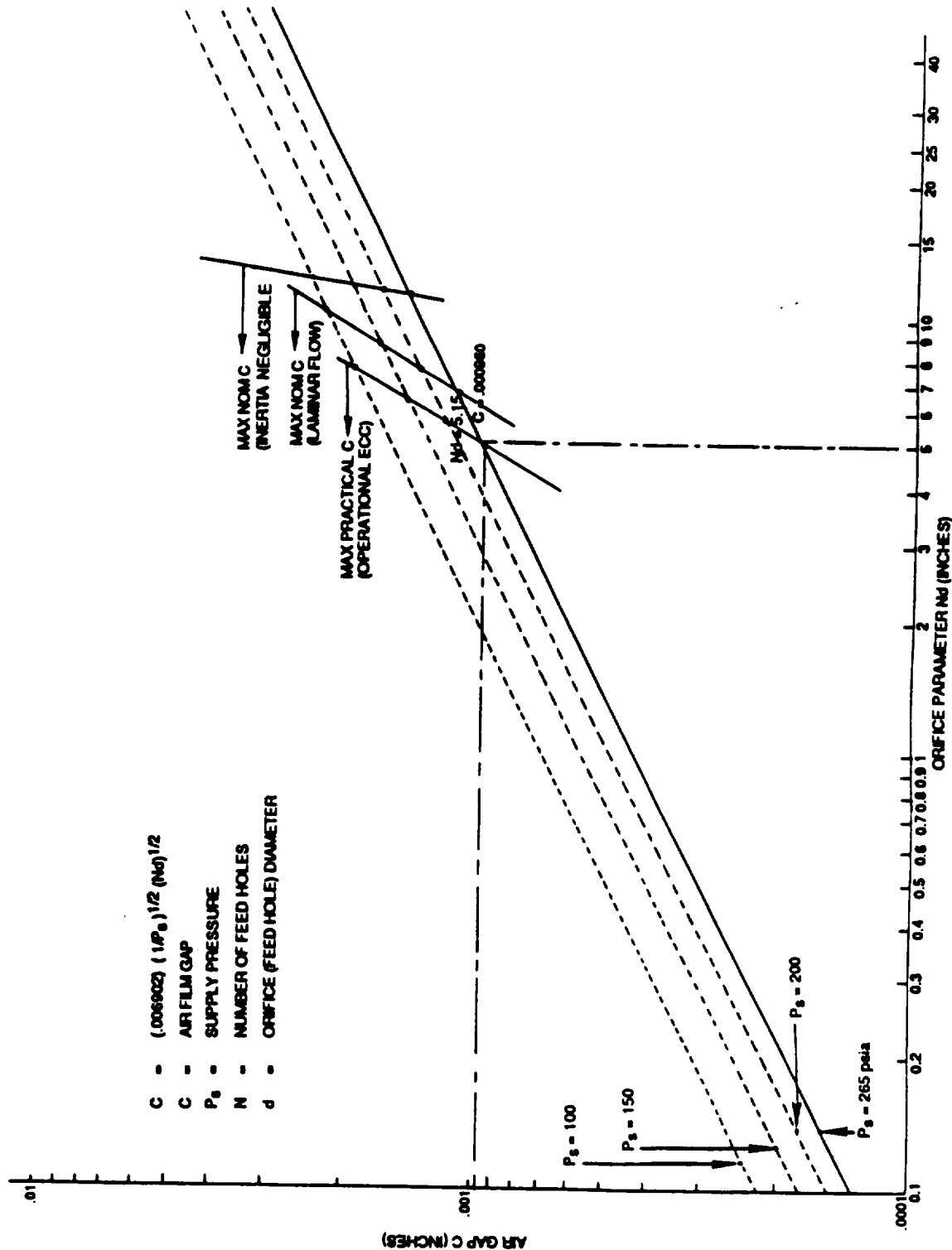
#### Concept Details (Contd)

Once the bearing geometry and air supply pressure have been chosen, the air gap must be calculated. In general, the larger the air gap the higher the flow rate and the faster the flow velocity. It is necessary to keep the flow velocity low in order to satisfy the assumptions applied to derive the design data, which are used to design the bearing. The accompanying figure shows the maximum air gap that may be chosen (based on the above flow constraints) for several different pressures. A lower air supply pressure would allow a larger air gap, but the bearing would no longer be capable of reacting the axial pressure load or, if the bearing 'wrap' angle were increased (so the bearing could react the axial load) a bore smaller than 31.0 in. diameter would be necessary and the bearing would get heavier.

Since all flow calculations are based on a centered air bearing, the gap must be chosen somewhat smaller than the maximum allowable. This gives allowance for the change in gap size when the bearing is loaded. Therefore a gap of .000960 in. was chosen.

All other bearing parameters follow in a straightforward manner after the foregoing decisions have been made. A summary of all of the bearing parameters can be found later in this subsection.

### ORIFICE PARAMETER VS AIR GAP



### Feasibility Assessment

Building the SOFIA air bearing will be a task comparable to building the KAO air bearing. In the time since the KAO bearing was built there have been advances in machining technology. However, no one has ever built a spherical air bearing the size of SOFIA. In fact the KAO air bearing is still the largest of its kind.

The difficulty with the SOFIA bearing is in maintaining such precise dimensional and geometric tolerances on such a large mechanical element. All the technology exists to do this, but the tooling may not. Building the SOFIA bearing will be a time consuming and relatively expensive project. It is felt that this component is a strong candidate for early prototyping.

### **FEASIBILITY ASSESSMENT**

- SIMILAR TO KAO AIR BEARING, BUT MUCH LARGER WITH TIGHTER TOLERANCES
- ADVANCES IN MACHINING TECHNOLOGY ENHANCE FEASIBILITY
- AIR BEARING OF THIS SIZE HAS NOT BEEN DEMONSTRATED
- TOOLING FOR PRECISE TOLERANCES MAY NOT EXIST
- STRONG CANDIDATE FOR EARLY PROTOTYPING

## **Summary**

The accompanying chart summarizes the SOFIA air bearing parameters. The most notable items are as follows: 1) the large size of the bearing - 48.0 in. diameter; 2) The small air gap -.000960 in.; 3) the weight of the subsystem - currently 17,860 lbs., and 4) the large power requirements for the compressed air.

The SOFIA air bearing will be a difficult and relatively costly piece to manufacture. When completed, it would be by far the largest spherical air bearing of its kind. Due to the high mass of the current (solid) design concept, further efforts will be needed to lightweight the structure.

### SOFIA AIR BEARING SUMMARY

#### GEOMETRY

BEARING DIAMETER = 48.00 IN

EFFECTIVE LENGTH = 28.80 IN

ROTATION = + AND - 4 DEGREES AZIMUTH AND LOS (UNLIMITED IN ELEV.)

NOMINAL AIR GAP = .000960 IN.

#### FEED HOLES

2 ROWS OF 40 FEED HOLES (80 HOLES TOTAL) EQUALLY SPACED @ 9 DEGREES AROUND PERIPHERY, 7.584 IN. EITHER SIDE OF VERTICAL CENTERLINE

FEED HOLE DIAMETER = .0410 IN.

#### AIR REQUIREMENTS

FLOW = 40 SCFM MINIMUM

PRESSURE = 265 PSIA

DEW POINT = 20°F < MINIMUM AMBIENT

POWER REQUIRED TO COMPRESS AIR = 6,500 WATTS MINIMUM

#### BEARING STIFFNESS

RADIAL STIFFNESS =  $1.481 \times 10^8$  LBS/IN.

AXIAL STIFFNESS =  $3.286 \times 10^7$  LBS/IN.

#### OPERATING ECCENTRICITY RATIO

RADIAL = .140

AXIAL = .330

#### WEIGHT

BALL = 7,304 LBS

SEAT = 10,560 LBS

TOTAL SUBSYSTEM = 17,860 LBS

#### MATERIAL

INVAR

#### Open Issues/Major Concerns

The most pressing concern with the SOPIA air bearing is that no detailed stress analysis has yet been performed. Analysis shows that the bending stiffness of the bearing is sufficient for the bearing to act as a structural element in the system. However, no analysis has yet been performed which substantiates that the bearing will maintain its figure when subjected to loads. Since the air gap is so small, the bearing can not be allowed to deform very much before the performance is degraded.

The weight of the bearing is presently estimated to be 17,860 lbs. (7,300 lbs. for the ball and 10,560 lbs. for the seat). Obviously this is extremely heavy. Further design work must be done to try and reduce the weight, with a goal of 13,500 lbs.

The thermal gradient across the bulkhead (and bearing) may be a potential problem for SOPIA, but a review of the KAO air bearing thermal analysis reveals that this thermal gradient may not be a big problem after all. Indeed, the bearing may not necessarily be made from Invar if careful thermal planning is incorporated into the design, which may help reduce weight.

## **SOFIA AIR BEARING OPEN ISSUES/MAJOR CONCERNS**

- A DETAILED STRESS ANALYSIS NEEDS TO BE DONE
- WEIGHT MUST BE REDUCED
- GOOD THERMAL DESIGN IS REQUIRED, ESPECIALLY FOR ALTERNATE MATERIALS
- PROTOTYPING/TECHNOLOGY DEMONSTRATION DESIRABLE

## **SOFIA Vibration Isolation System**

### **System Requirements and Assumptions**

The SOFIA vibration isolation system is required to attenuate aircraft vibrations from the telescope structure while minimizing the total deflection of the structure. The system must also support a weight of 30,000 lb (telescope and air bearing).

In designing the vibration isolation system it was assumed that the center of mass of the telescope structure will be located at the center of the air bearing and that the isolators will be mounted in a vertical plane also passing through the center of the air bearing. This configuration decouples the modes of vibration and allows the system to be analyzed as a single degree of freedom system in each of the three translational directions.

Assumptions were also made about the magnitude of vibration the isolators experience from the aircraft during tracking. These assumptions were based on 747SP data provided by Boeing and on data directly recorded on the KAO.

## **VIBRATION ISOLATION SYSTEM**

### **I. REQUIREMENTS**

- A. ISOLATE TELESCOPE SYSTEM FROM AIRFRAME VIBRATIONS**
- B. MINIMIZE STRUCTURAL DEFLECTION**
- C. SUPPORT SYSTEM WEIGHT OF 30,000 LBS**

### **II. ASSUMPTIONS**

- A. ISOLATORS MOUNTED IN PLANE OF SYSTEM MASS CENTER  
(DECOUPLED MODES OF VIBRATION IN THREE TRANSLATIONAL DIRECTIONS)**
- B. AIRCRAFT RESPONSE BASED ON BOEING 747SP AND C141 DATA**

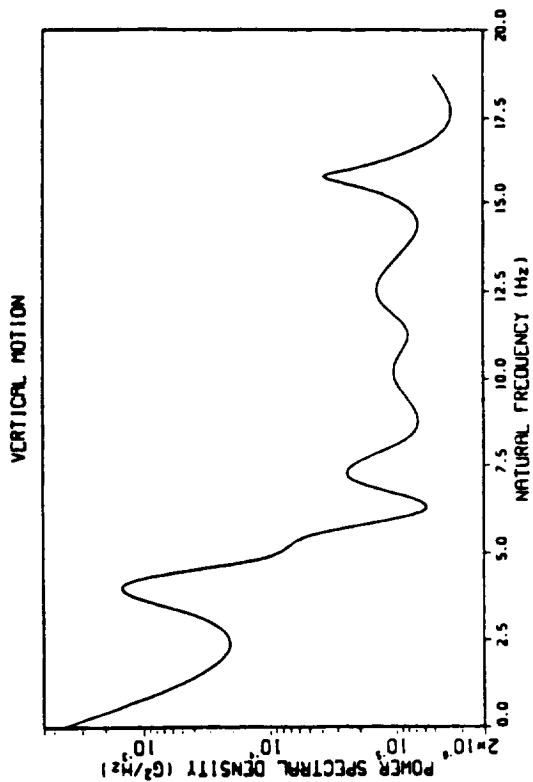
### Power Spectral Densities of the Boeing 747SP

In order to begin design of the vibration isolation system it was necessary to determine the estimated accelerations transmitted to the isolation system from the aircraft. These estimates were based on the power spectral density (PSD) plots provided by Boeing. These plots were recorded at several locations throughout the aircraft for various flight conditions. Vibration analysis for SOFIA was based on the Boeing PSD plot for body station 310 at an altitude of 40,000 ft. and a speed of  $M=0.8$ , this data being the closest to the proposed isolation system location and flight conditions for SOFIA during tracking.

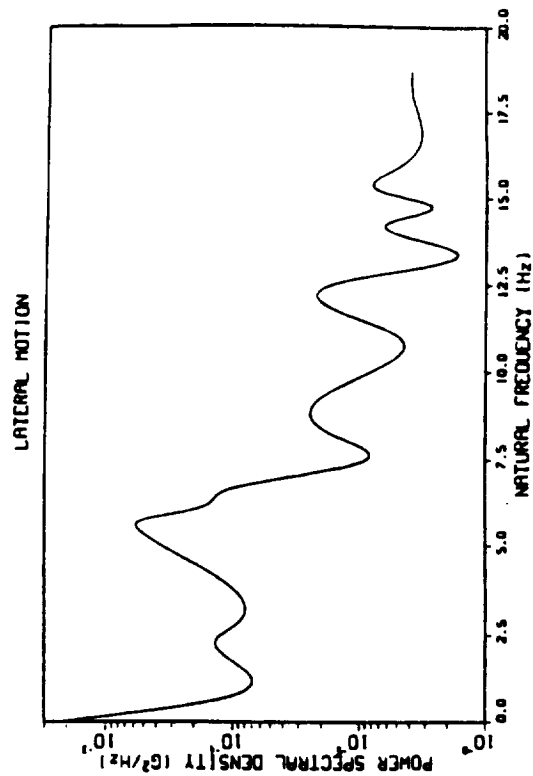
Because the PSD's were random plots, a cubic spline curve fitting was performed to generate continuous functions representative of the PSD's in the lateral and vertical directions as shown here.

The data provided by Boeing was somewhat limited. For more accurate determination of aircraft response, additional vibration data should be taken from a 747SP. New PSD plots should be recorded over a larger frequency range in each of the three translational directions and at a location on the aircraft closer to the proposed location of the vibration isolation system (appr. station 700).

### BOEING 747SP POWER SPECTRAL DENSITY



ALTITUDE - 40,000ft SPEED - Mach 0.8



ALTITUDE - 40,000ft SPEED - Mach 0.8

### Structural Response to Random Vibration

The PSD functions generated from the Boeing 747SP plots were used to determine the RMS accelerations  $[F(t)]$  for various damping factors and natural frequencies of the vibration isolation system. The area under the PSD curve represents the variance (square of the standard deviation) of the probability distribution curve for the random vibration. For a single degree of freedom system, the mean square response of the structure to a random excitation is the integral of the product of the PSD and complex frequency response for the structure. The value resulting from the square root of the integration was multiplied by a peak response factor of 3 to account for 99.7% of the random vibrations based on a Gaussian probability distribution. This information was used to determine the frequencies that experience the lowest levels of acceleration.

## STRUCTURAL RESPONSE TO RANDOM VIBRATION

$$F^2(t) = \int_0^{\infty} [H(f)H^*(f)]S(f) df$$

$$F(t) = \sigma [F^2(t)]^{1/2}$$

where:

$F^2(t)$  = Mean Square Response of the structure to a random excitation ( $g^2$ )

$F(t)$  = RMS Mean Acceleration

$\sigma$  = Peak Response Factor (probability of  $F(t)$ )

$S(f)$  = Power Spectral Density Function ( $g^2/\text{Hz}$ )

$[H(f)H^*(f)]$  = Complex frequency response function for the structure (single degree of freedom)

$$\text{where: } H(f) = \frac{1}{[1 + (f/f_n)^2] - i[2\xi(f/f_n)]}$$

$$H^*(f) = \frac{1}{[1 - (f/f_n)^2] - i[2\xi(f/f_n)]}$$

$f_n$  = Natural Frequency of Structure (Hz)

$\xi$  = Damping Coefficient

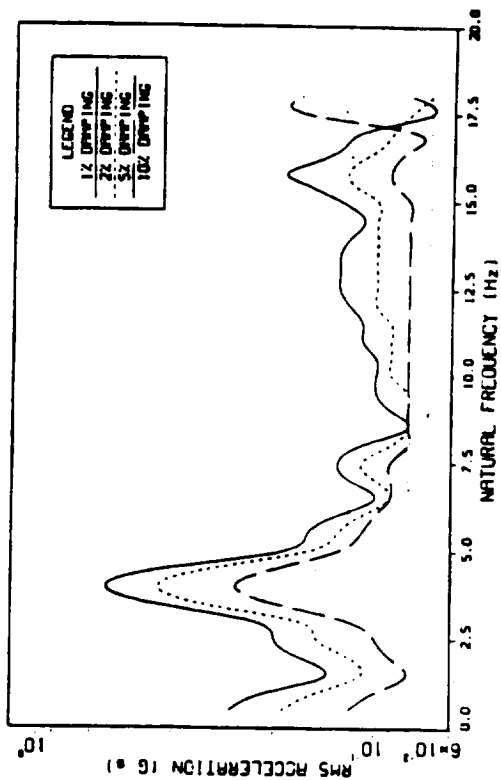
### **RMS Acceleration**

The resulting RMS accelerations were plotted versus natural frequencies for damping factors of 1%, 2%, 5% and 10%. Using these plots optimal design frequencies were determined for the lateral and vertical directions.

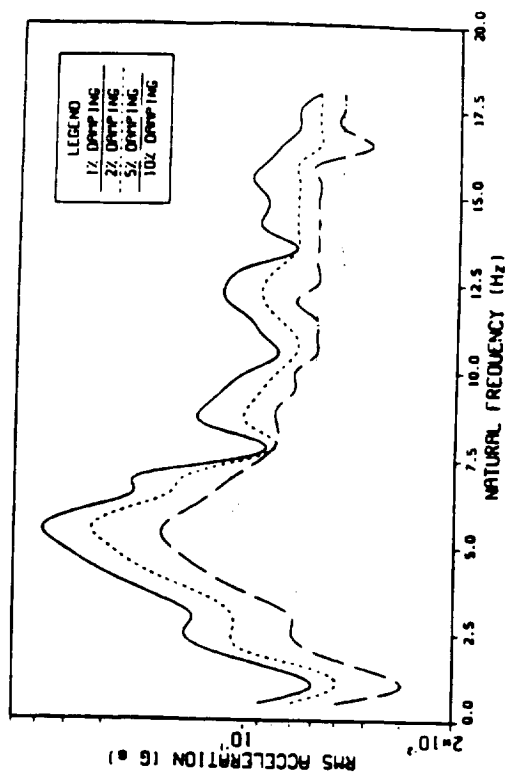
These plots show that the isolation system should have a resonant frequency below 3 Hz in the vertical direction and 5 Hz in the lateral direction, preferably 1 Hz and 1.5 Hz in the vertical and lateral directions respectively. However, due to other system requirements such as deflection, these low frequencies were not feasible and the system was designed to approximately 2.5 Hz in each of the translational directions.

### BOEING 747SP ACCELERATION DUE TO RANDOM EXCITATION

VARIABLE DAMPING



VERTICAL MOTION AT 40,000 ft M=0.8



LATERAL MOTION AT 40,000 ft M=0.8

### Aircraft Response

The desired natural frequencies for minimal transmitted acceleration previously determined were based on standard flight conditions of the 747SP. For further analysis it was necessary to incorporate the effects on vibration due to opening the telescope cavity on the 747SP. To determine these effects vibrational data was collected on the Kuiper Airborne Observatory. The data was recorded to establish a correlation between the vibration on the aircraft near the telescope before and after deploying the fence and opening the cavity. PSD's were recorded in three locations, below the two rear isolators on the airframe and directly on the left rear isolator. Based on these plots and for simplification of analysis, white noise was assumed. The ratios of tracking to door closed white noise vibrations were then determined.

The square root of the area under the Boeing 747SP PSD's were then calculated to determine the RMS g accelerations for the aircraft during normal flight at 40,000 ft and a speed of 0.8 Mach. These accelerations were then multiplied by the square root of the ratio of tracking/door closed vibration for the KAO to determine the estimated RMS accelerations that will be transmitted to the vibration isolation system on the 747SP during tracking.

It should be noted that the lateral and fore/aft levels of vibration were assumed equal based on data collected from the KAO.

### BOEING 747SP ESTIMATED VIBRATIONAL ACCELERATIONS

	Ratio Tracking/Door Closed (g <sup>2</sup> /g <sup>2</sup> )	Area Under PSD Curve Normal Flight (g <sup>2</sup> )	RMS Acceleration Normal Flight (g's)	RMS Accelerations During Tracking (g's)
<u>C141<sup>1</sup></u> (0-100 Hz)				
Vertical	17	0.00012	0.011	0.045
Lateral	14	0.00032	0.018	0.067
Fore/Aft	45	0.00008	0.0089	0.067
<u>BOEING 747SP</u> (0-20 Hz)				
Vertical	20 <sup>*</sup>	0.0022	0.047	0.21 <sup>*</sup>
Lateral	15 <sup>*</sup>	0.0013	0.036	0.14 <sup>*</sup>
Fore/Aft <sup>1</sup>	-	-	-	0.14 <sup>*</sup>

<sup>1</sup>Values based on actual test data taken on the KAO

<sup>2</sup>Estimated acceleration for 747SP = (normal flight accelerations) X (tracking/door closed ratio)<sup>1/2</sup>

<sup>3</sup>No fore/aft data was provided by Boeing for the 747SP in the fore/aft direction; Lateral and fore/aft accelerations assumed equal based on C141 data

<sup>4</sup>Ratio of tracking/door closed vibrations for 747SP is assumed equivalent to that for the C141

### Transmitted Accelerations

The transmitted accelerations (through the isolators) were calculated by the following equation

$$G = \sqrt{n/2} D F_n Q^{1/2}$$

where:  $D$  = Magnitude of white noise from the input PSD's. The average level of white noise for the 747SP was determined by dividing the area under the PSD curve ( $g^2$  RMS accelerations) by the 20 Hz frequency range spanned by the PSD.

$$D_{LAT} = 0.0013/20 = 65 \mu g^2/Hz$$

$$D_{VER} = 0.0022/20 = 110 \mu g^2/Hz$$

$$F_n = \text{Natural frequency of the isolation system}$$

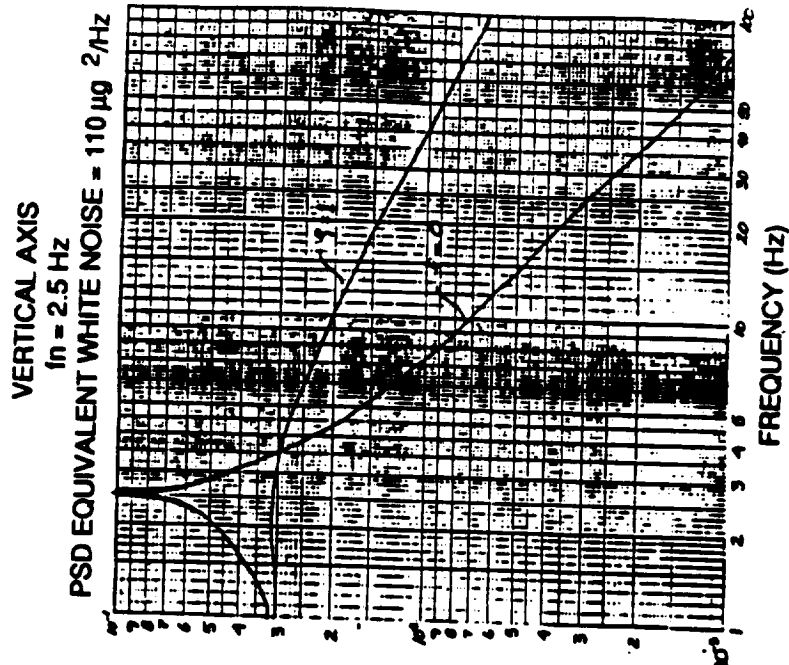
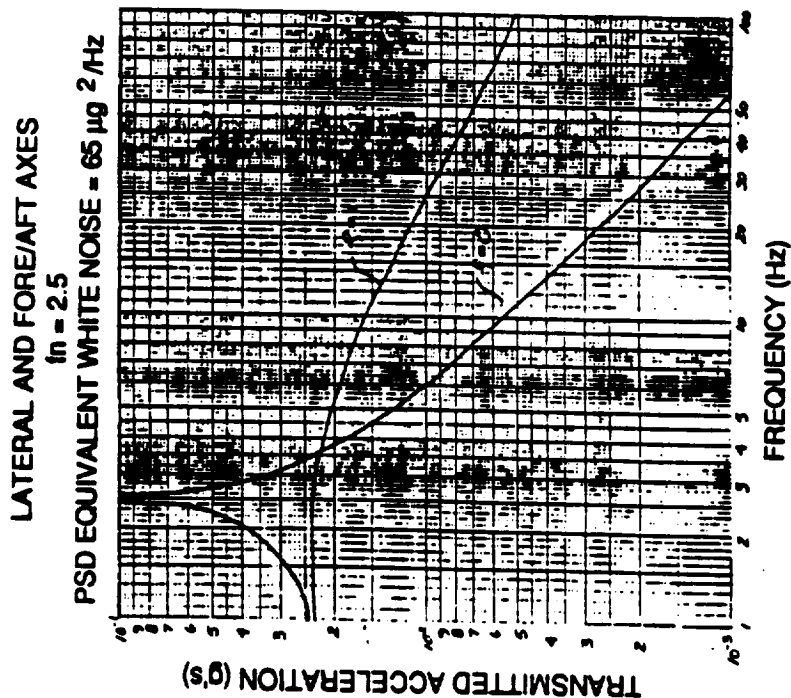
$$Q = \text{Transmissibility} = [1 + (2 \xi r)^2]^{1/2} / [(1 - r^2)^2 + (2 \xi r)^2]^{1/2}$$

where:  $r$  = Design frequency/system natural frequency

$$\xi = \text{Damping factor}$$

The results shown are for a 2.5 Hz system plotted over a frequency range of 0-100 Hz for the vertical and horizontal planes. For a given frequency, a corresponding acceleration can be read from the plot. This value is the estimated acceleration that will be transmitted through the isolation system to the telescope at that frequency.

## TRANSMITTED ACCELERATIONS FOR EQUIVALENT WHITE NOISE PSD'S



## **Proposed System**

The proposed vibration isolation system will consist of four pneumatic isolators all located in a plane parallel to the aft cavity bulkhead and through the mass center of the telescope system. The pneumatic isolators are semiactive in their axial directions. A height control valve will be used to react any input displacements by inputting/removing air to the surge tank when a displacement occurs. Four isolators provide higher center of mass stability and reduce static deflection. Placing the isolators about the center of mass permits decoupling of vibrational modes.

Pneumatic isolators were chosen because of their ability to attenuate low frequency vibration. It is desirable to make the natural frequency as low as possible in order to move the resonant peaks to lower frequencies and for better attenuation of high frequencies. Rubber or composite pads have natural frequencies between 5-10 Hz which is in the region where the magnitude of vibration is the largest; therefore, they would act as amplifiers rather than isolators. Metal springs are impractical due to their large static deflections.

Each pneumatic isolator has an axial stiffness,  $k$ , and a radial stiffness,  $k/4$ . (The radial stiffness is based on the shear stress in the elastomeric members.) Connected in series are the internal snubbers which, when the system is active, minimally affect the system stiffness.

Four air springs will be connected parallel to the fore/aft axis at the same locations as the pneumatic isolators. These springs will increase the stiffness in that direction as well as minimize deflection. In addition, air springs attenuate approximately 95% of the vibrations above 7.5 Hz.

The total stiffness in each direction is a combination of the stiffness for the isolators, internal snubbers and air springs.

The proposed isolation system will have two modes of operation, the "tracking" mode and the "jocked" mode. In the first mode, the isolators will attenuate frequencies above 2.5 Hz up to a maximum acceleration of 0.25g's. If the 0.25g limit is reached the isolators will enter the locked mode where the internal snubbers will isolate frequencies above 7 Hz. These internal snubbers will restrict deflections up to the maneuvering/gust limit loads. If the acceleration reaches the level of the crash limit loads, external snubbers will prevent metal to metal contact.

## **VIBRATION ISOLATION SYSTEM PROPOSED SYSTEM**

- A. FOUR SEMI-ACTIVE PNEUMATIC ISOLATORS
  - (1) MINIMUM OF THREE ISOLATORS FOR SYSTEM STABILITY
  - (2) PNEUMATIC ISOLATORS PROVIDE LOWER SYSTEM NATURAL FREQUENCY
  - (3) ISOLATORS INCORPORATE RELAXATION DAMPING PRINCIPLES
  - (4) ISOLATORS ARE ACTIVE IN AXIAL DIRECTION
  - (5) AXIAL STIFFNESS - 5,000 LB/IN.      RADIAL STIFFNESS - 1250 LB/IN.
- B. FOUR PASSIVE PNEUMATIC ISOLATORS - ISOLATE FORE/AFT VIBRATIONS
  - AXIAL STIFFNESS - 3750 LB/IN.      RADIAL STIFFNESS - 1875 LB/IN
- C. INTERNAL SNUBBERS - ISOLATE VIBRATIONS WHEN SYSTEM IS LOCKED (SYSTEM LOCKS WHEN LOADS EXCEED 0.25g's AND DURING TAKE-OFF AND LANDING)
  - AXIAL STIFFNESS - 46,140 LB/IN.      RADIAL STIFFNESS - 23,070 LB/IN.
- D. EXTERNAL SNUBBERS - PREVENT METAL TO METAL CONTACT BETWEEN BULKHEAD AND STATOR RING ASSEMBLY DURING EXTREME LOADS (DESIGNED FOR CRASH LOADS)

### Proposed System (Contd)

The system stiffness (K) is determined from the natural frequency (Fn) of the system:

$$K = (2\pi)^2 m F_n^2$$

Where the system weight (m) is 30,000 lb. This stiffness will be provided by the isolators, air springs and internal snubbers.

The maximum deflection (d) of the system for each mode of operation is based on the total stiffness of the isolators and the maximum acceleration (a) in that mode as follows:

$$d = F/K = ma/K$$

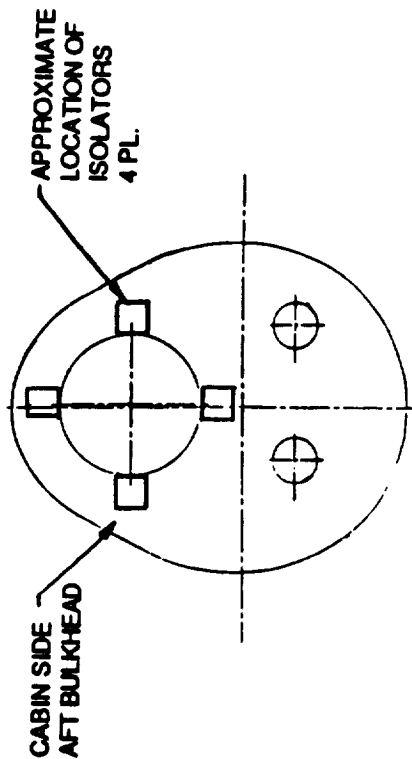
During tracking the maximum travel occurs when a 0.25g limit load is reached. This acceleration results in a  $\pm 0.375$  in. deflection in the vertical, lateral and fore/aft directions.

When the system is locked the pneumatic isolators act as rigid supports and deflection is governed by the stiffnesses of the internal snubbers and air springs. In this mode the system is designed to gust/maneuvering limit loads. At a maximum vertical acceleration of + 3.04 g's upward the system will travel 0.625 in., for 1.04 g's downward the deflection will be 0.2 in. In the lateral direction a  $\pm 0.63$  g acceleration results in  $\pm 0.3$  in. deflection. The fore/aft deflections for  $\pm 0.20$  g's are  $\pm 0.1$  in.

For crash loadings the 4.5 g upward load and the 2.0 g downward load produce 0.93 in. and 0.41 in. deflections respectively. The  $\pm 1.5$  g lateral load results in  $\pm 0.31$  in. deflection. And the 3.5 g fore load and 1.5 g aft load produce 1.0 in. and 0.42 in. deflections respectively. The maximum forward crash load is 9 g's. Beyond 3.5 g's external snubbers will isolate vibration and prevent metal to metal contact. Therefore the total maximum deflection in any direction will be less than 1 in.

Aircraft limit loads are based on specifications outlined by Owen Illinois report: 'Specification for a vibration isolation system...' F(6)-700-051-014-1600A; Nov. 13, 1970. These limit loads are also specified in SOFIA PD-2000.

### PROPOSED VIBRATION ISOLATION SYSTEM



	Natural Frequency (Hz)	Stiffness (Lb/in)	Maximum Acceleration (g's)	Detection (in)
<b>TRACKING*</b>				
Vertical	2.48	19,000	0.25	0.375
Lateral	2.48	19,000	0.25	0.375
Fore/Aft	2.54	19,700	0.25	0.375
<b>LOCKED SYSTEM*</b>				
Vertical	6.9	146,000	+3.04 -1.04	0.625 0.20
Lateral	6.9	146,000	0.63	0.30
Fore/Aft	5.9	107,000	0.20	0.10
<b>CRASH LIMIT LOADS*</b>				
Vertical	6.9	146,000	+4.5 -2.0	0.93 0.41
Lateral	6.9	146,000	1.5	0.31
Fore/Aft	5.9	107,000	+3.5 <sup>b</sup> -1.5	1.00 0.42

\*Stiffness and natural frequency determined by pneumatic isolators, air springs and internal snubbers  
 \*Stiffness and natural frequency determined by air springs and internal snubbers  
 \*Maximum forward crash load is 8 g's; External snubbers minimize motion beyond 1" deflection and 3.5 g's (forward direction)

### **Damped Pneumatic Springs**

The design of the isolators will incorporate relaxation damping principles. The system consists of compressed air flowing from a surge tank into a load carrying chamber through an orifice which acts like a capillary flow restrictor. The size of the orifice will determine the amount of system damping as well as the stiffness and natural frequency of the system. This controls the magnitude of vibration transmitted to the telescope.

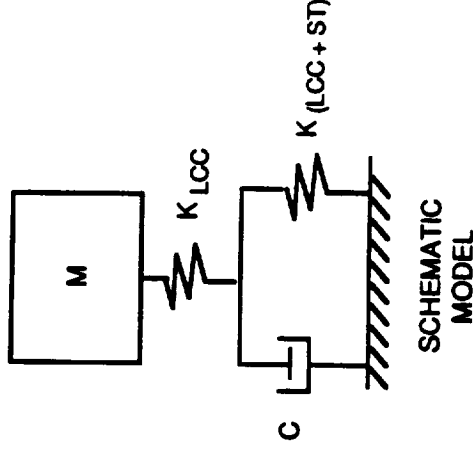
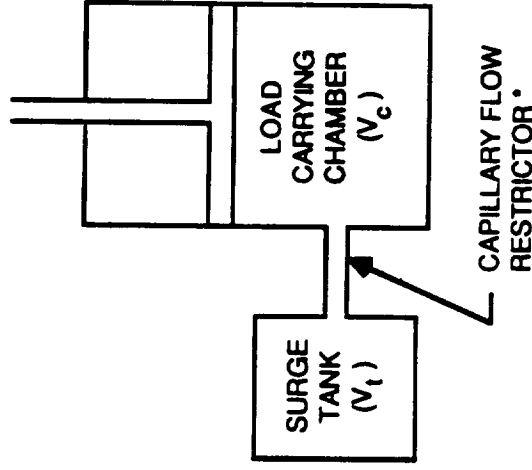
By varying the orifice size, the system's damping factor can be controlled and an optimum damping can be found for which resonant response is a minimum. Small variations in the orifice can result in pronounced variations in resonant frequency. When the orifice is small, flow is highly restricted and the system characteristics (i.e., natural frequency and stiffness) will be determined by the pressure and volume in the load carrying chamber.

For a larger orifice the restrictions are lowered and the system is determined by the pressure and volume of both the surge tank and the load carrying chamber.

By using a variable orifice in the design an optimum orifice size can be determined upon installation based on actual aircraft response.

Additional control of the system stiffness and natural frequency is available by varying the air pressure within the surge tank.

## DAMPED PNEUMATIC ISOLATORS



### • ORIFICE SIZE DETERMINES DAMPING

#### SMALL ORIFICE - HIGH RESTRICTION

$$C = \infty \quad K_{\infty} = 2\pi P A^2 / V_c = K_{LCC}$$

where:

$C$  = DAMPING CONSTANT

$K$  = ISOLATOR STIFFNESS

$n$  = 1.4 FOR COMPRESSED AIR

$P$  = PRESSURE IN CYLINDER

$V_c$  = LOAD CARRYING CHAMBER VOLUME

$A$  = PISTON AREA

#### LARGE ORIFICE - LOW RESTRICTION

$$C = 0 \quad K_0 = 2\pi P A^2 / (V_c + V_t) = \frac{(K_{LCC})(K_{ST})}{K_{LCC} + K_{LCC + ST}}$$

where:  $V_t$  = SURGE TANK VOLUME

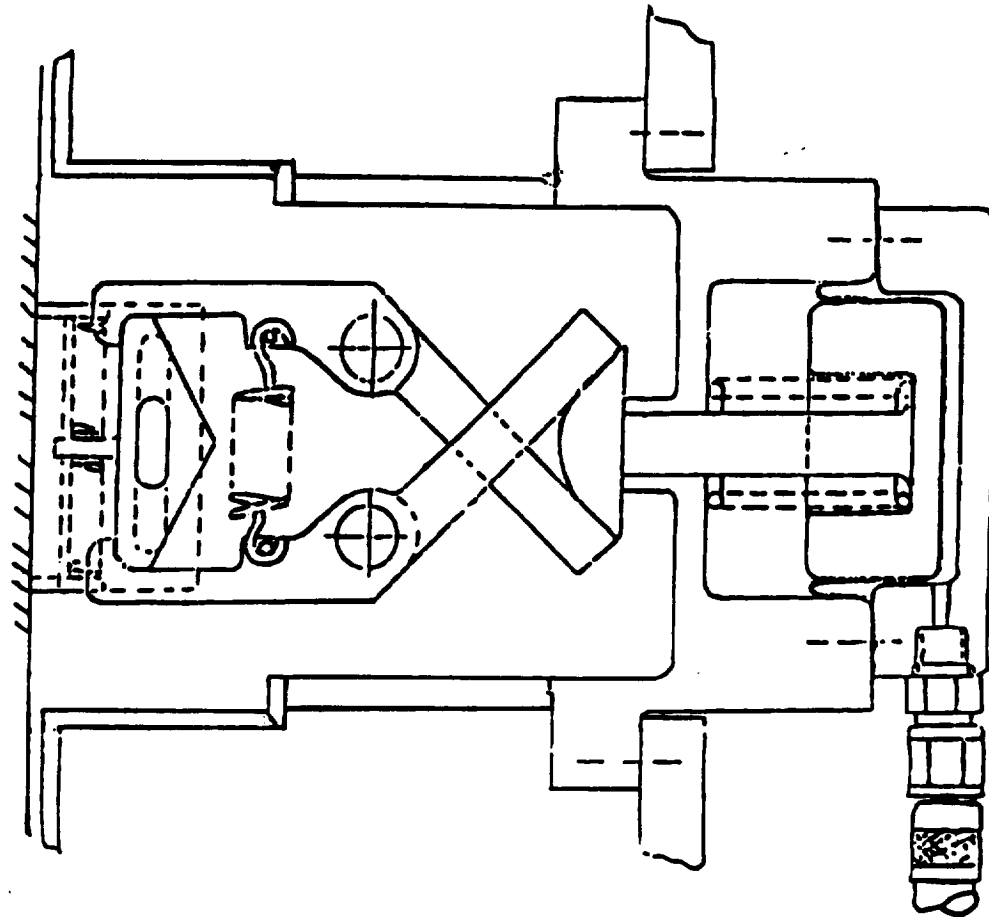
### Locking Mechanism

A possible design for the locking mechanism on SOFIA is one similar to that on the KAO. The piston unlocks when compressed air is pushed against the bottom of the mechanism creating a normal force sufficient to open the clamp that grips the piston. As the inner chamber fills with air, the piston rises above the caging mechanism at which point the mechanism closes.

For sudden impacts above 0.25 g's, the piston will lock back into the caging mechanism. To release the piston compressed air must again be supplied to the locking mechanism. This will require manual control for resetting.

This design is feasible; however, additional possibilities should be investigated.

## CROSS-SECTIONAL VIEW OF CAGING MECHANISM (ISOLATOR LATCHED)



### Concerns/Risks

Several areas requiring further analysis and tradeoff activity still exist for the SOFIA vibration isolation system, although basic feasibility of a candidate concept has been demonstrated. In the area of aircraft response, 747SP PSD's should be measured at approximately station 700, with additional fore-aft data included. The Boeing provided data is somewhat suspect, as one would expect lower vibration levels for a 747SP than for the C141 (KAO) measured data. It is suggested that additional vibration data be collected for the unmodified 747SP considering the added requirements; further analysis of the cavity-open environment for SOFIA is warranted.

Due to the possibility that the telescope system center of mass may be offset from the vibration isolation system plane, further analysis of the resulting coupled modes and additional torques may be needed, once telescope mass properties are settled. Additional loads not yet analyzed are those generated by the telescope system maneuvering torques; these should be added for consideration in any follow-on effort.

A final tradeoff that should be performed in greater depth is the "soft system vs. stiff system" problem, whose resolution depends on the relative levels of structure-borne vs aero-generated loading. The aero loading on the telescope is largely unknown at present, depends on several factors, and is a good candidate for near-term analysis or testing.

### **CONCERNS/RISKS**

#### **A. AIRCRAFT RESPONSE**

- (1) 747SP DATA PROVIDED BY BOEING WERE FOR BODY STATION 310 OF THE AIRCRAFT WHEREAS THE TELESCOPE WILL BE MOUNTED AT BODY STATION 700
  - (2) BOEING PSD'S PROVIDED VIBRATION DATA IN THE LATERAL AND VERTICAL DIRECTIONS ONLY
  - (3) BOEING PSD'S PRESENTED LEVELS OF VIBRATION FOR THE 747SP WHICH WERE HIGHER THAN THOSE FOR THE C141; MASS TO WING AREA RATIOS WOULD SUGGEST OTHERWISE
  - (4) EFFECTS OF THE OPEN CAVITY ARE BASED ON C141 DATA ONLY
- B. POTENTIAL MASS CENTER OFFSET WOULD RESULT IN COUPLED MODES OF VIBRATION AS WELL AS ADDITIONAL TORQUES ACTING ON THE ISOLATION SYSTEM
- C. TORQUERS PRODUCE REACTION FORCES THROUGH VIBRATION ISOLATION SYSTEM
- D. TRADE OFF BETWEEN MINIMIZING RESPONSE TO AIRCRAFT VIBRATION, SOFT SYSTEM BEING MORE ADVANTAGEOUS, TO MINIMIZING RESPONSE TO AERO LOADS WHERE A STIFF SYSTEM WOULD BE BETTER

## Pointing and Control Subsystem

### General Pointing System Requirements

The SOFIA telescope system will be a three-axis controlled system with inertial stabilization and tracking capability. During normal on-axis tracking, it is envisioned that tracking will only be necessary in the elevation (ELEV) and azimuth (AZIM) axes, inasmuch as rotation around the line-of-sight (LOS) will have little or no effect on pointing accuracy. During offset tracking, however, when the guide target will be offset from the tracked target at the telescope focal plane, tracking in the line-of-sight axis will be required as well. This requirement will necessitate the use of two stars of sufficient visual magnitude, or other equivalent technique, to properly determine rotation about this boresight axis.

The Telescope System Requirements Document (PD-2000) envisions three separate tracking cameras and their respective optics, with switching provisions for appropriate selection of control signals from any one of them. Minimum tracking sampling rate is specified to be 10 Hertz. The combined 3-axis drift rate of the telescope under stabilization loop control only is limited to a maximum of 0.5 arcseconds/second.

The telescope elevation axis is required to have a coarsely settable range of travel between and including 20 and 60 degrees above the horizon (unvignetted). The dynamic range for each of the three axes was selected to be  $\pm 4$  degrees but this figure may be modified by trade studies relative to constraints imposed by aircraft modification issues. Pointing accuracy of 0.15 arcsec is required for stars of visual magnitude 13 and brighter. Nodding capability up to 20 arcminutes is required, with a settling time (to 1% of nod amplitude) of 2 seconds of time or less for a 5 arcminute nod. Slewing capability up to 24 arcminutes per second in any combination of motions in the three axes of rotation is specified.

Mapping capability using various motion patterns is required as well as capabilities for storage of up to four different targets for nodding purposes. Dead reckoning accuracy of 15 arcminutes or better is required along with a maximum acquisition time of 30 seconds.

### GENERAL POINTING SYSTEM REQUIREMENTS

- 3 DEGREES OF FREEDOM  
ELEV: 20° TO 60° COARSE RANGE (UNVIGNETTED)  
ELEV, AZIM, LOS  $\pm 4^\circ$  DYNAMIC RANGES
- 3-AXIS STABILIZATION
- AZIMUTH AND ELEVATION TRACKING ON AXIS  
AZIM, ELEV, AND LOS TRACKING OFF AXIS
- TRACKING ERROR SIGNALS DERIVED FROM ANY OF THREE CAMERAS
- TRACKING SAMPLING RATE  $\geq 10$  Hz
- DRIFT RATE  $\leq 0.5$  ARCSEC/SEC WITH TRACKER LOOPS OPEN
- TELESCOPE NODDING  
0 TO 20 ARCMIN IN ANY DIRECTION  
SETTLING TIME (FOR 5 ARCMIN NOD) 2 SEC  
ACCURACY 1% OF AMPLITUDE (OR 0.15 ARCSEC)  
 $M_V = 13$  OR BRIGHTER
- SLEWING  
0 TO 24 ARCMIN/SEC IN ANY DIRECTION
- AUTOMATED MAPPING USING CIRCULAR, SPIRAL, AND RASTER PATTERNS
- STORED TARGET LOCATION FOR NOD FUNCTION (UP TO 4) WITH AUTOMATED SCHEDULES  
OR OPERATOR INITIATED TARGET SELECTION
- DEAD RECKONING ACCURACY BETTER THAN 15 ARCMIN
- ACQUISITION TIME  $\leq 30$  SECONDS AFTER ESTABLISHMENT OF HEADING AND COARSE ELEVATION

### Tracking and Acquisition Requirements

Three television type cameras with their associated light gathering optics and necessary electronics are envisioned to be incorporated into the system. The Focal Plane Tracker is defined as that sensor system which would be sharing the optical path of the main telescope with the science instrument when used. The Fine Tracker and the Acquisition cameras would both be mounted as appendages to the main telescope and be boresighted to it. Each unit is required to be able to be used as a tracker providing attitude error correction signals to the pointing control system, including the LOS axis rotation signal derived from the relative orientation of two stars in the field-of-view (FOV). The Focal Plane Tracker and the Fine Tracker are both required to be capable of properly detecting stars of visual magnitude +13 and brighter with FOVs of 8 and 30 arcminutes respectively. To aid in the operational acquisition process, a roughly 3.5 to 1 zooming capability is called for in the case of the Acquisition unit at a slightly relaxed requirement for detectable targets of + 11 visual magnitude for the widest FOV.

Pointing stability/accuracy requirements using these sensor units vary from 0.15 arcsecond RMS to 15 arcseconds RMS. Current levels of analyses and assessments indicate that the 0.15 arcsecond RMS stability requirement is somewhat ambitious, that the  $\pm 10$  arcsecond accuracy figure could be tightened, and that the 15 arcsecond RMS stability requirement will need to be studied further.

Offset tracking requirements are that the system be able to electronically offset the guide target from the science target anywhere within the respective FOVs of the tracking units and that the Fine Tracker be, in addition, mechanically gimbaled to provide up to 38 arcminutes of offset in azimuth and elevation. Offset pointing stability of 1.0 arcsecond is required when utilizing the Focal Plane Tracker. Further study is necessary to determine practicable offset pointing requirements when either of the other two camera systems (Fine Tracker and Acquisition) is used.

Much progress is currently being made in the CCD camera arena. It appears that a reassessment of the requirements here will be made in the near future when more is known about the capabilities of the new sensor units.

## **TRACKING AND ACQUISITION REQUIREMENTS**

- FOCAL PLANE TRACKER
  - 2-STAR GUIDANCE CAPABILITY  $M_V = +13$  AND BRIGHTER
  - FOV = 8 ARCMIN
  - ELECTRONIC OFFSET IN AZIM AND ELEV =  $\pm 4$  ARCMIN
  - POINTING STABILITY 0.15 ARCSEC RMS (ON AXIS)
  - OFFSET POINTING STABILITY 1.0 ARCSEC RMS
- FINE TRACKER
  - 2-STAR GUIDANCE CAPABILITY  $M_V = +13$  AND BRIGHTER
  - FOV = 30 ARCMIN
  - GIMBALLED MECHANICAL OFFSET  
38 ARCMIN IN AZ AND ELEV
  - POINTING ACCURACY  $\pm 10$  ARCSEC (ON AXIS)
  - OFFSET POINTING TBD
- ACQUISITION CAMERA
  - 2-STAR GUIDANCE CAPABILITY
  - REMOTE ZOOMING
  - FOV  $\sim 9^\circ \times 12^\circ$  FOR  $M_V = +11$  AND BRIGHTER
  - FOV  $\sim 2.5^\circ \times 3.5^\circ$  FOR  $M_V = +13$  AND BRIGHTER
  - ELECTRONIC OFFSET IN AZ AND EL  $\pm 1/2$  FOV
  - POINTING ACCURACY 15 ARCSEC RMS (ON AXIS)
  - OFFSET POINTING STABILITY TBD

### Pointing and Stabilization:

Since the basic telescope configuration is now conceptualized as an extrapolation of the Kuiper Airborne Observatory (KAO) telescope, there will be five levels of control working together to ultimately achieve the absolute and relative pointing accuracies required of the telescope. At the first level, the basic aircraft will provide the baseline attitude and heading control. Periodic updates to the autopilot by the pointing system supervisory controller will assist in improving heading accuracy. A telescope system vibration isolation system will be incorporated to remove a substantial amount of aircraft translational vibrations transmitted by the structural members tied directly to the aircraft. Translational motions by themselves will contribute very little to the error budget; however, the vibratory effects on the telescope structural members and on the centers of mass of various large salient parts can be significant and will be minimized by the isolation system. This system would play the part of the second level of stabilization control. The third level will be provided by an air bearing system similar to that installed in the KAO. This bearing, with its inherent low rotational friction coupling between rotor and seat, will be most important in attenuating a large portion of the attitude excursions expected of the aircraft.

The dynamic travel range requirement for the telescope ( $\pm$  or  $\sim$  4 degrees in elevation, azimuth and line-of-sight) is highly dependent on the expected aircraft attitude stability provided by its autopilot system. Establishment of data supporting a high probability that aircraft excursions could be kept within about  $\pm$  or  $\sim$  1 degree after the expected modifications and installation of the telescope would assist greatly in reducing this range requirement and permit a larger aperture telescope to be considered. However, the higher LOS range requirement may still be needed to compensate for field rotation during observation of extended objects; this issue is presently under review.

Inertial stabilization using rate integrating gyros for feedback will be the fourth level of control. Video tracker feedback control loops will represent the fifth level and provide the final corrections for lower frequency perturbations. It is assumed for this conceptual phase that no image motion compensation using small-mirror articulation techniques will be necessary.

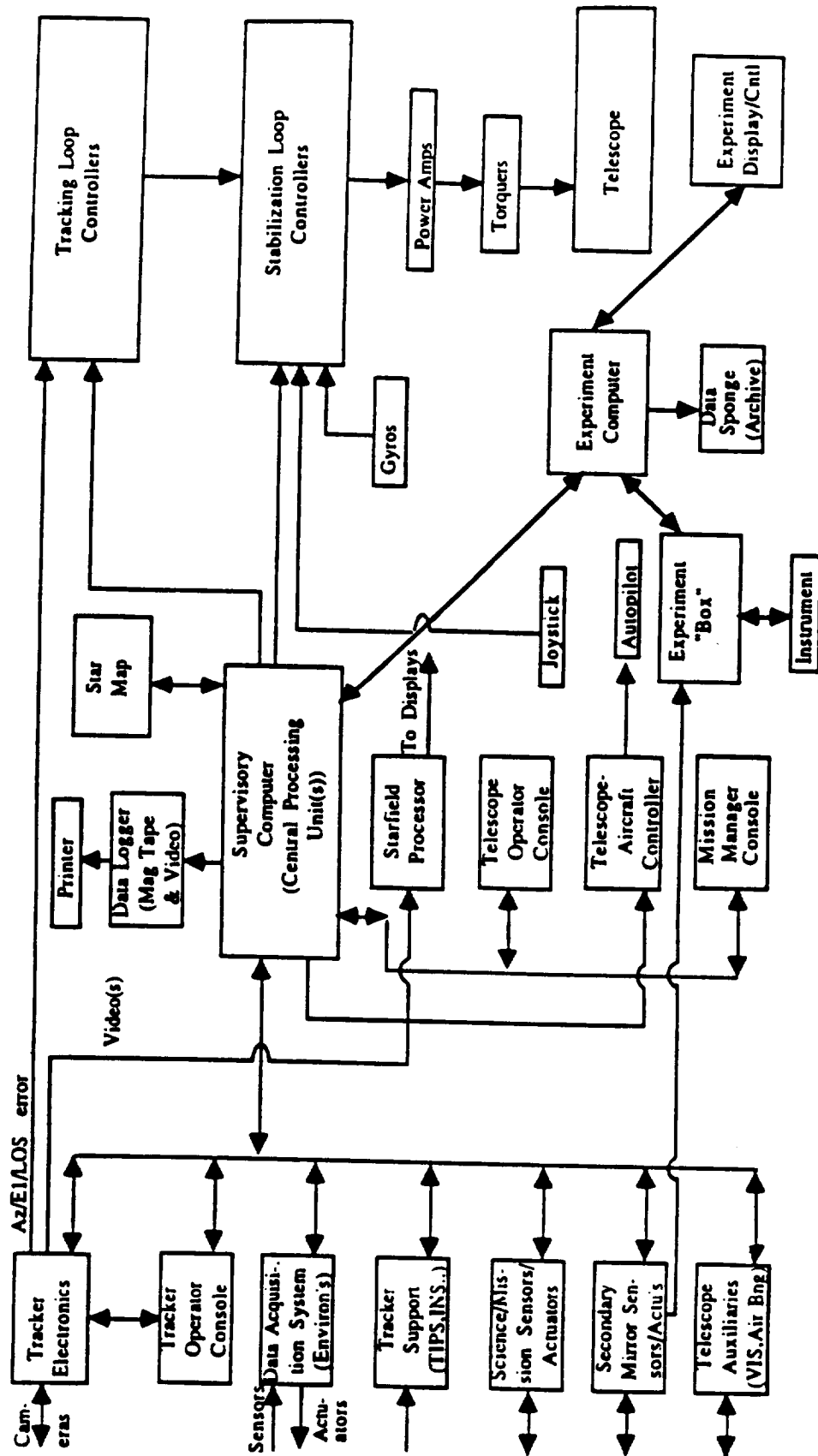
## **POINTING AND STABILIZATION CONTROL LEVELS**

- AIRCRAFT
- VIBRATION ISOLATION SYSTEM
- AIR BEARING
- GYRO STABILIZATION CONTROL SYSTEM
- VIDEO TRACKING CONTROL SYSTEM

### Control System Block Diagram

The control system block diagram shows the interaction between various units within the telescope system. Central to the system is the Supervisory Computer. This unit is considered to basically be a system command generator and data handler. Information from the various system sensors, data acquisition system, the control consoles and the experiment computer are stored and acted upon (as preprogrammed) to provide the pointing system, the console monitors, the data logging system, the aircraft, and the experiment with the proper signals at the proper times. Special functions such as automatic periodic telescope focus compensation, automatic LOS axis drift compensation (using other techniques not requiring the star tracker in use to determine field rotation), and star-field recognition are envisioned to be incorporated.

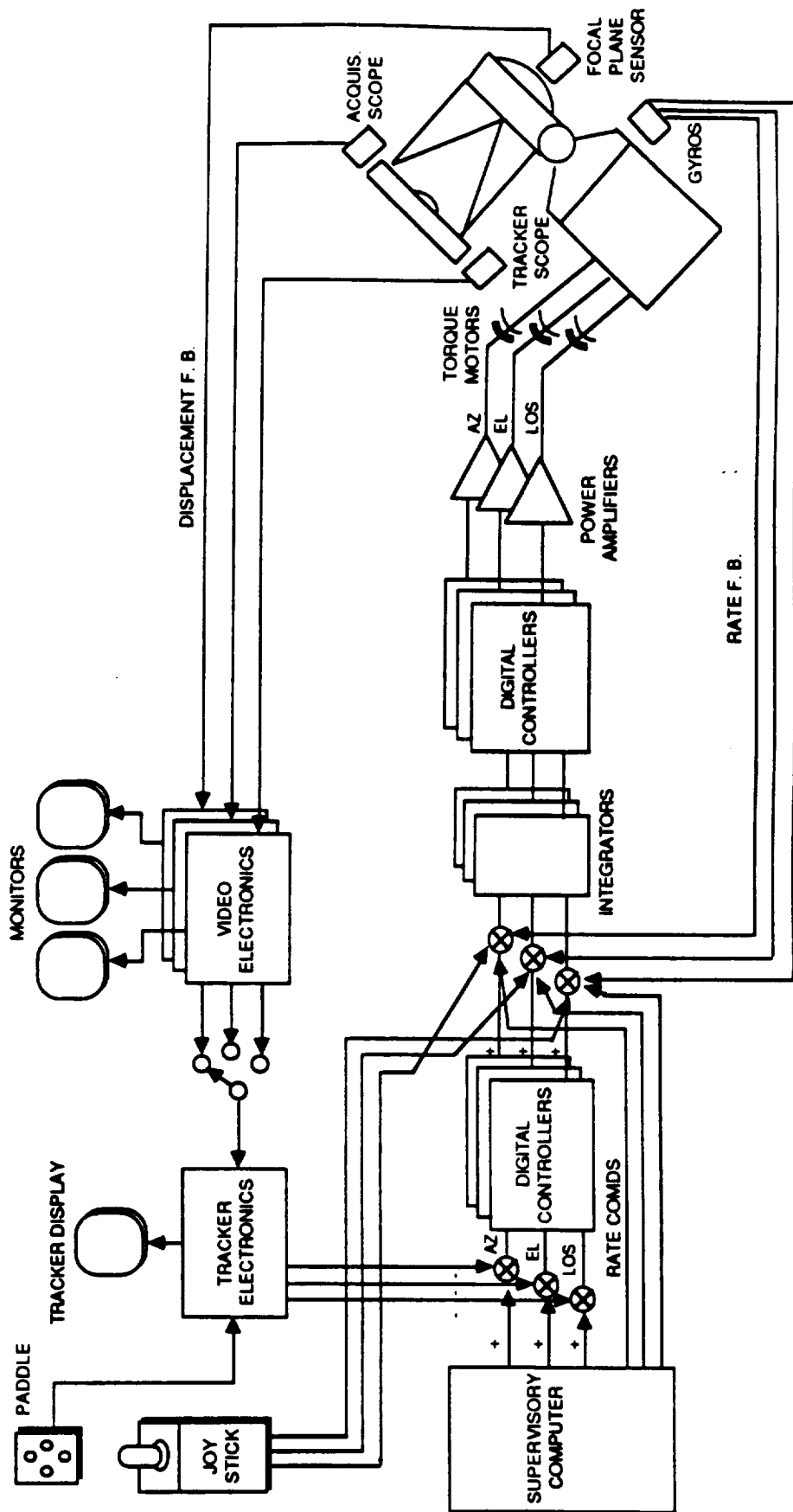
### CONTROL SYSTEM BLOCK DIAGRAM (TOP-LEVEL)



### Three-Axis Pointing System

The Three-Axis Pointing System diagram portrays the envisioned configuration consisting of three orthogonal axes of baseline control. Each axis would be associated with its own spherical-segmented torque motor as the prime mover within a rate stabilization servo loop. The digital controllers would be PID (Proportional, Integral, Derivative) controllers. There would be three selectable target sensor channels, as mentioned earlier, to be utilized appropriately in the various modes of operation. Using any of the three channels, the tracker electronics system would provide either two- or three-axis output signals depending on the availability of two or more targets in the given field of view, and depending on whether the on-axis or offset tracking mode of operation is being used. Whereas the joystick would provide the means for real-time operator control of the telescope attitude, the supervisory computer would act as a higher-level-of-automation command generator for any of the individual tracking or stabilization loops.

### 3-AXIS POINTING SYSTEM



### **Moments of Inertia**

The Telescope System Mass Moment of Inertia (MOI) matrix shown on the opposite page indicates several notable points: The MOIs range between 42 million and 137 million lb-in<sup>2</sup>; the elevation axis is associated with the lowest and the Line-of-Sight axis with the highest MOI; and although cross axis mass coupling in the X-Y and X-Z axes are reasonable, the coupling in the Y-Z axes combination is very high at about 24 percent.

### TELESCOPE STRUCTURE MOMENT OF INERTIA

	AZ	EL	LOS
MASS AXIS	X	Y	Z
X	$1.265 \times 10^8$	$4.576 \times 10^5$	$3.846 \times 10^5$
Y		$4.232 \times 10^7$	$-1.004 \times 10^7$
Z	SYM		$1.374 \times 10^8$

ALL VALUES ARE IN UNITS OF LB-IN<sup>2</sup>

### Pointing System Perturbations

Seven specific perturbations to the pointing and control system are identified, with aircraft attitude excursions, aircraft vibration and open port aerodynamic loading being the more significant disturbances to the system. Current requirements call for aircraft excursions to be limited to 0.5 degree magnitude in roll, pitch and yaw. The actual excursions as seen by the control system will depend significantly on the effectiveness of the air bearing in the baseline design to attenuate this undesirable input. Preliminary studies show that we may expect about 0.1-0.2 g RMS of vibration input from the aircraft to the base of the vibration isolation system. The magnitude and frequency content of this disturbance reaching the telescope will clearly be dependent on the characteristics of the isolation system. Aerodynamic loading poses the largest threat to the pointing system in that current estimates show up to 2000 lb-ft of peak torque being imposed on the telescope system. The other four expected perturbations are estimated to be relatively small and may be compensated for by the system with much less difficulty.

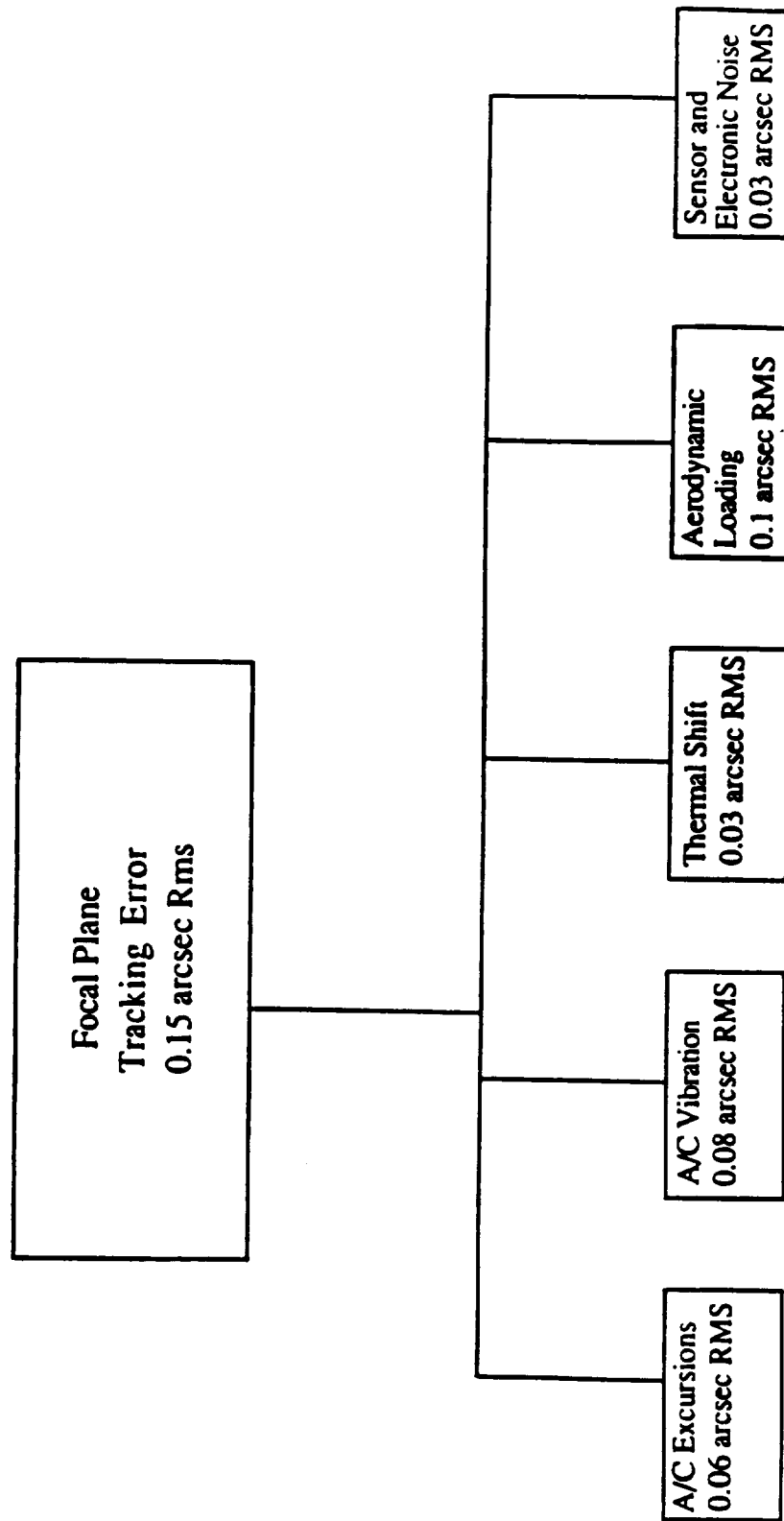
### **POINTING SYSTEM PERTURBATIONS**

- AIRCRAFT ATTITUDE EXCURSIONS
- AIRCRAFT VIBRATION
- OPEN PORT AERODYNAMIC LOADING
- THERMALLY INDUCED MISALIGNMENTS
- TRACKER NOISE AND QUANTIZATION ERROR
- GYRO NOISE
- ELECTRONIC NOISE AND DRIFT

### **Tracking System Error Budget**

The tracking system error budget, as depicted, uses 0.15 arcseconds RMS as the total stability error. This assumes that focal plane tracking, using a sensor sharing the main optics focal plane, is the mode of operation for which this budget applies. Note here that the bulk of the total budget is allocated to aerodynamic loading, aircraft vibration and aircraft excursions.

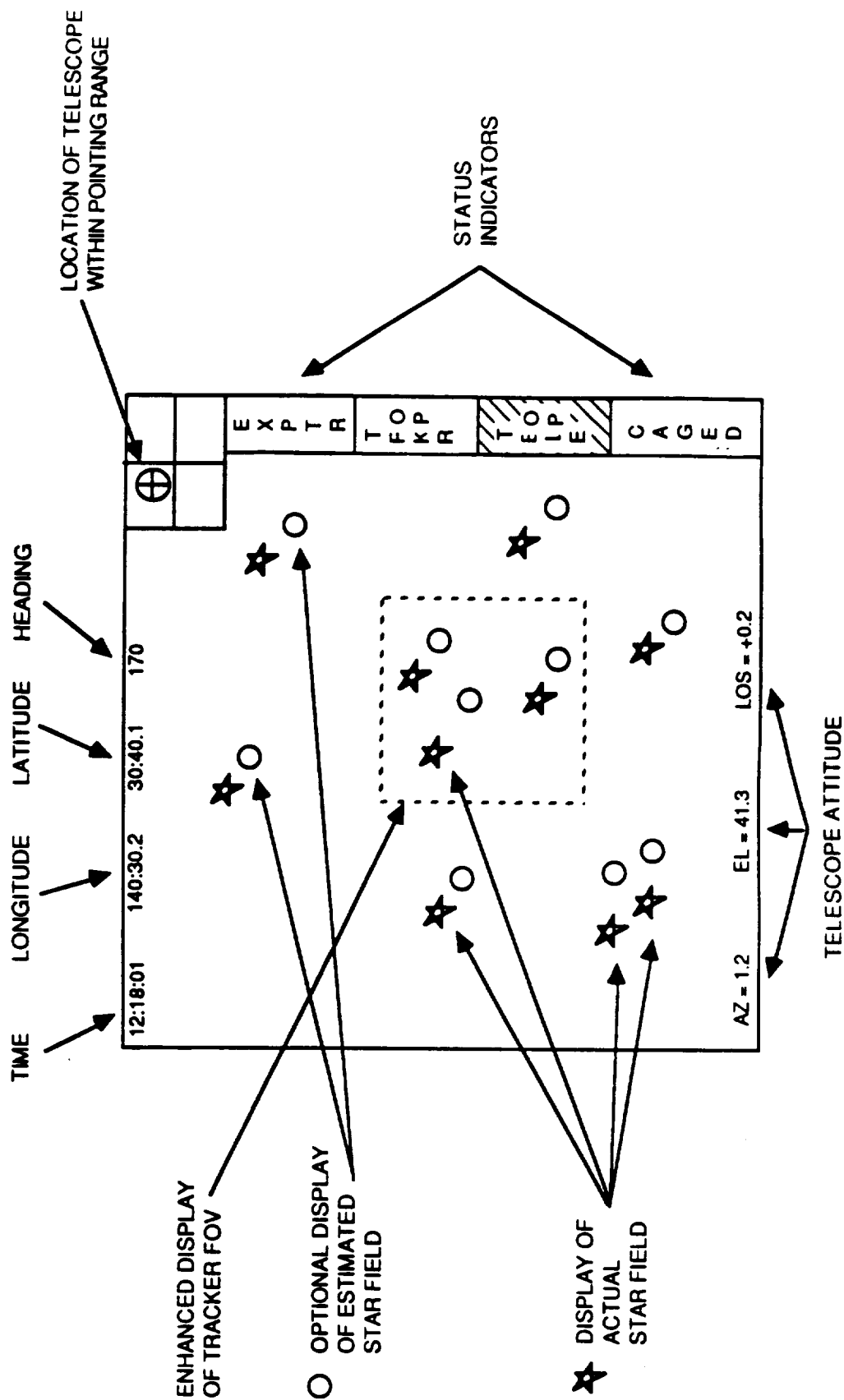
## TRACKING SYSTEM ERROR BUDGET



### Acquisition Camera Display

This illustration portrays a conceptual acquisition monitor display design. Its salient feature would be a wide field-of-view with an enhanced outline display of the Fine Tracker field. The wide angle will allow the telescope system operator to easily identify star fields and, using a "mouse," joystick or similar input control device, efficiently orient the telescope to place the target for selected tracking within the enhanced tracker block. Concepts for additional acquisition aids include a pre-computed arrangement of the estimated star field displayed with the star for tracking pre-located at the boresight cross-hairs. The actual star field would then conceivably be easily moved to overlay the estimated star set by operator pointing of the telescope. Other informational aids include the time of day, longitude, latitude, heading, telescope attitude relative to the aircraft, operation mode status, and a graphic display at the right top corner showing the position of the telescope relative to its travel envelope.

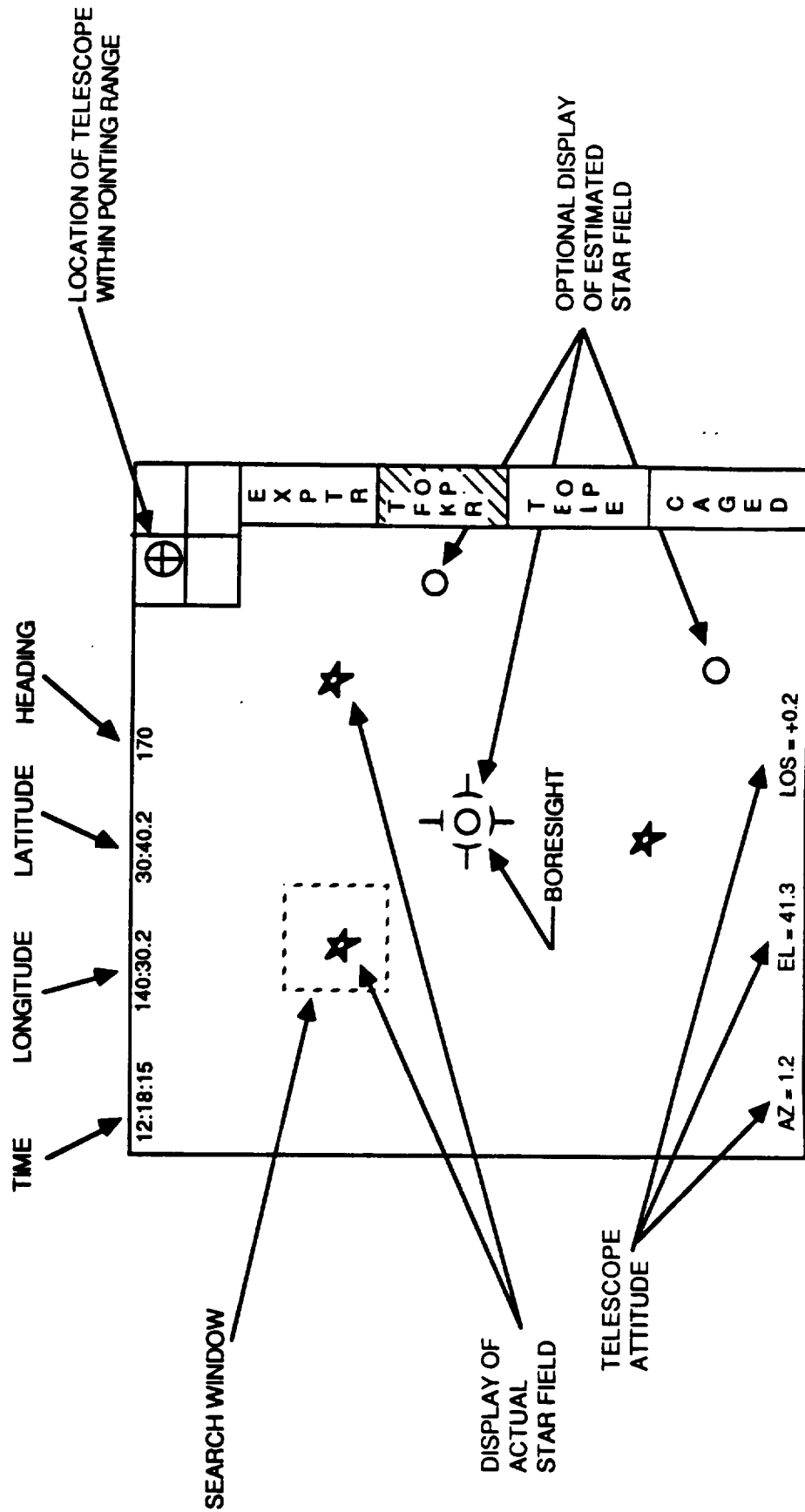
### ACQUISITION CAMERA DISPLAY



### Telescope Tracker Display

As similarly described for the Acquisition Camera Display, this chart illustrates some concepts which may be incorporated into the video monitoring systems to improve in-flight operation of the airborne telescope. Some of the elements displayed on the acquisition monitor are duplicated here on the tracker monitor, i.e., those informational text and graphical status indicators laid out around the periphery of the monitor and the operator-selectable display of the estimated star field. The primary differences shown for the tracker unit are (1), the FOV represented by the screen would be considerably smaller than that of the acquisition monitor and (2) a "mouse" (or equivalent device) driven adjustable search window would be available for operator manipulation and capture of the intended target. Upon capture of the target during operation, the operator would initiate the track mode of operation, which would cause the system controls to automatically move and lock the target at the boresight position on the monitor or at any other selected offset point within the tracker FOV.

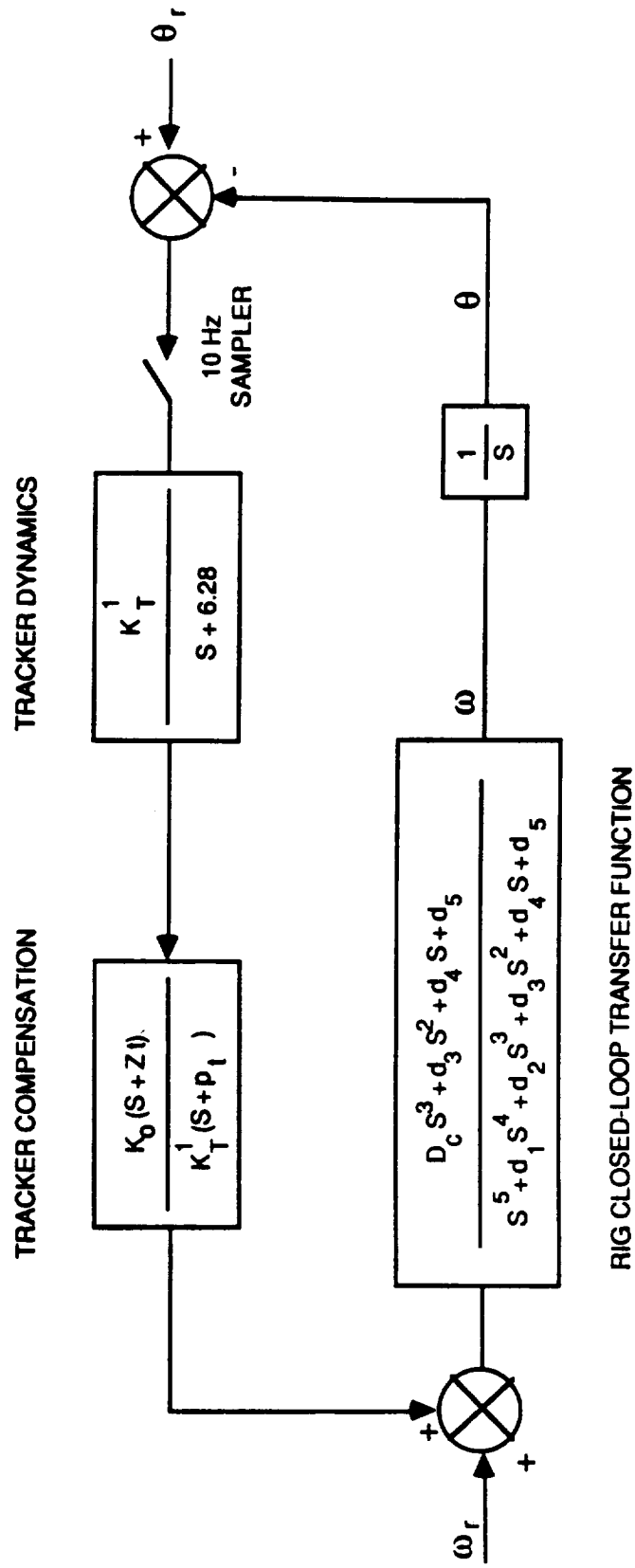
### TELESCOPE TRACKER DISPLAY



### Transfer Function Block Diagram

The transfer function block diagram illustrated here represents a typical single axis of the three-axis telescope pointing control system. This diagram depicts the tracking system as an outer control loop with a 1 Hz tracker time constant, a 10 Hz sampling rate and a generalized dipole compensation. The forward path basically represents the inner gyro stabilized loop, closed in rate and described by a transfer function of third order over a fifth order polynomial. In the conceptual design, working within the range of physically realizable quantities, the five independent coefficients of the forward path transfer function, the transfer function gains, plus the pole and zero locations of the tracker loop compensation dipole were systematically selected to provide acceptable simulated responses.

### TRANSFER FUNCTION REPRESENTATION OF OVERALL SYSTEM

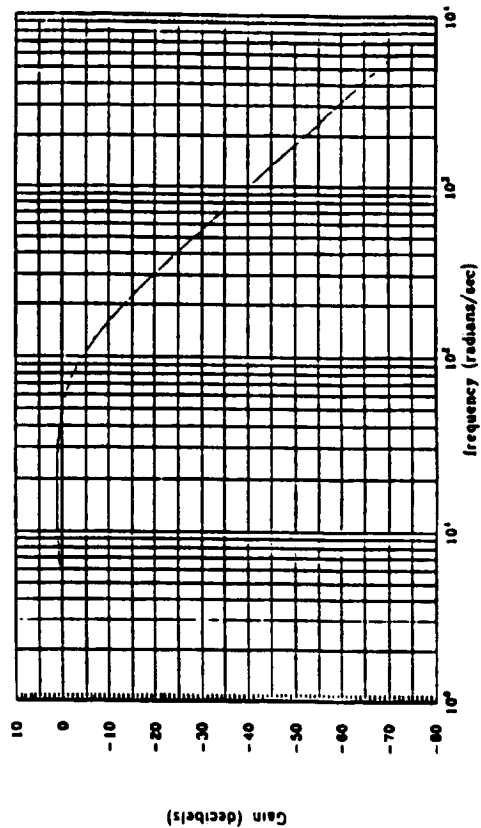


### **Frequency Response Magnitude and Phase**

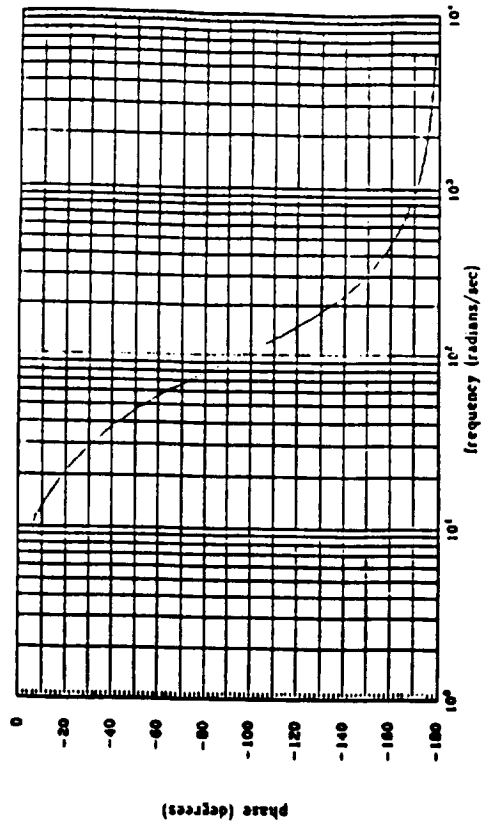
The facing two plots show the frequency responses of the system rate loop as conceptually designed, in magnitude and phase, respectively. Note that a system bandwidth of something more than 10 Hz is necessary and appears achievable.

### FREQUENCY RESPONSE OF RIG LOOP, CONTINUOUS MODEL (Bandwidth = 13.84 Hz)

(a) GAIN VERSUS FREQUENCY



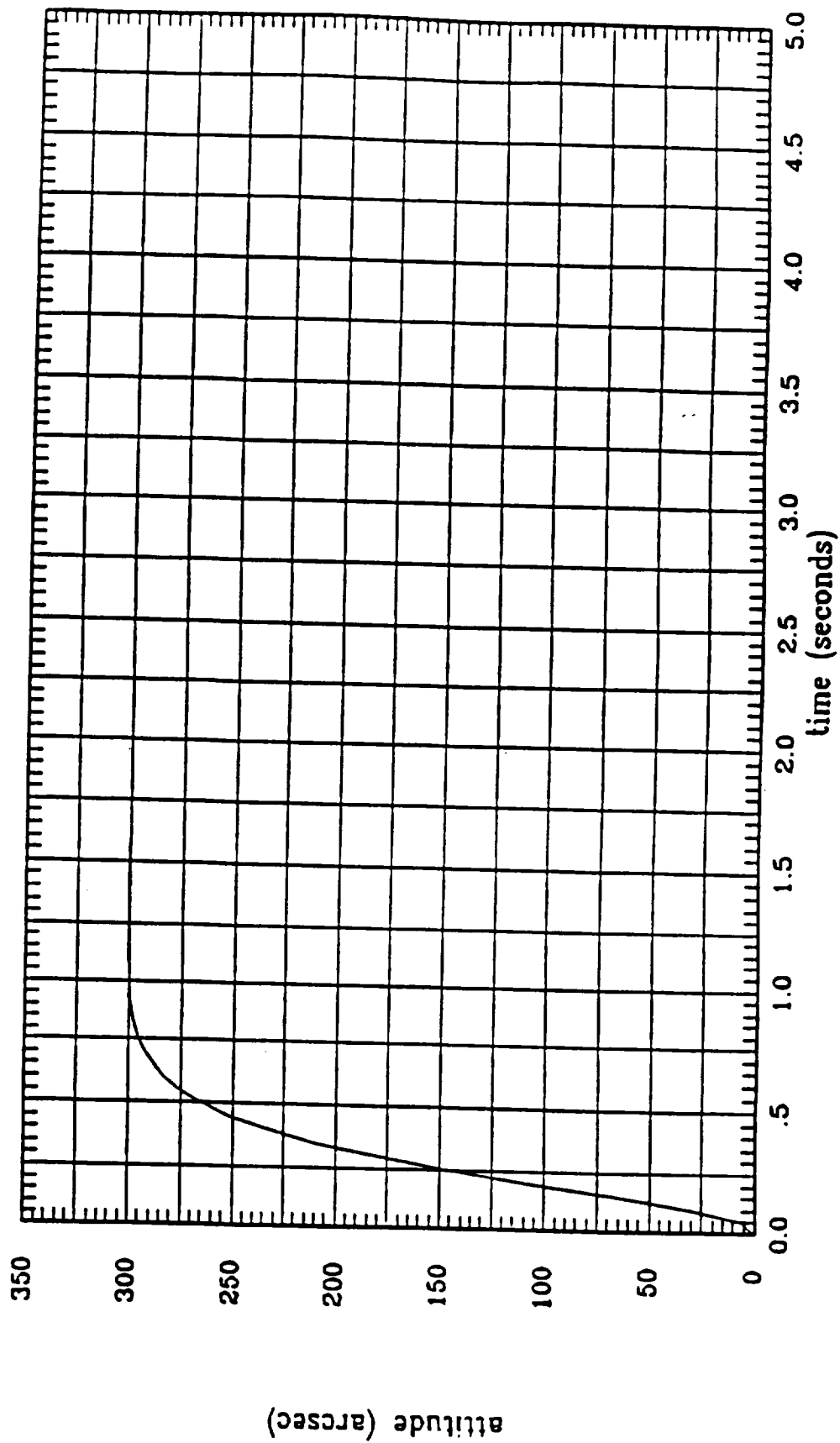
(b) PHASE VERSUS FREQUENCY



### Tracking System Step Response

The pointing control system with its tracker loop closed around a tuned rate loop (as depicted by the previous transfer function block diagram) was simulated after the proper choices of gains, coefficients and compensation pole-zero locations were made. The rise times obtained for 5 arcminute telescope nods easily met the required 2 seconds or less, as shown.

## STEP RESPONSE OF TRACKER LOOP (10 Hz SAMPLING FREQUENCY)



### Torque Motors Concept

With the baseline telescope system design utilizing a monoball air bearing for primary support, following the Kuiper Airborne Observatory (KAO) basic concept, the system prime movers tend naturally to be outgrowths of torque motors used in the current airborne observatory. Envisioned are extensions in design of the segmented spherical permanent magnet torquers. Preliminary estimates of aerodynamic torques felt by the telescope indicate the need for torque motors with RMS ratings of about 650 lb-ft and peak ratings of roughly three times that, or 1950 lb-ft. Motor manufacturers have been contacted and queried about the feasibility of motors of this size and configuration. Two of them responded with a fair amount of confidence that they could build segmented spherical motors, which were basic extensions of the ones being used by the KAO telescope, with peak torque ratings in the range of 2000 lb-ft and operating at radii of 3 to 4 feet. A possible alternative to the requirement for these large torques, of course, is to design the system using multiple smaller motors per axis. Although obviously complicating the mechanical design if the multiple motors per axis approach is taken, a side benefit would be that the large static attraction forces inherently associated with these permanent magnet motors (roughly 2500 pounds of force for the 650 lb-ft RMS units) would be reduced, thereby minimizing both the need for large special jigs and difficult maintenance procedures.

### **TORQUE MOTORS CONCEPT**

- MAGNETIC
- SEGMENTED SPHERICAL
- ESTIMATED REQUIRED RATED TORQUE = 650 LB-FT
- ESTIMATED REQUIRED PEAK TORQUE = 1950 LB-FT
- MOUNTED AT 3-4 FEET RADII
- EXTENSION OF CURRENT KAO DESIGN

### Tracker & Acquisition System Cameras

Results of conceptual studies show that cameras for the three Tracking and Acquisition (T&A) systems could be simple extensions of those in use on the KAO. New ISIT cameras with proper front-end optics would be the design choice at this point in time. Systems using CCD arrays are, however, beginning to show very promising signs. Usable error signals for pointing corrections have been obtained from CCD units working on very dim targets. Array uniformity, chip availability and long required integration times for faint objects, however, are some of the areas of concern being closely followed for developing improvements. Currently available on the market are relatively precise and fast video tracking electronic "black boxes". Significant efforts will be made to incorporate these off-the-shelf units or their future extensions to ease the perpetual need for increasing numbers of technical specialists and stringent documentation controls for one-of-a-kind systems.

### **TRACKER AND ACQUISITION SYSTEM CAMERAS OPTIONS**

- EXTRAPOLATIONS OF CURRENT KAO OPTICS
- ISIT TELEVISION CAMERAS
- CCD CAMERAS
- OFF-THE-SHELF TELEVISION TARGET TRACKERS

### Stabilization Loop Gyros

Several candidate gyroscopes were investigated for their applicability to the inertially referenced stabilization control loops on the SOFIA telescope system. Of these, five are listed in the chart and compared to the Honeywell GG334A, which is the model originally selected for the KAO system and now being phased out of that observatory because Honeywell stopped producing this gyro several years ago. Inasmuch as drift characteristics of the inertial reference sensors to be used in the stabilization loops significantly affect the attainable pointing accuracy and stability, of particular interest on the chart are the relative values of AIDR (Acceleration Independent Drift Rate), ASDR (Acceleration Sensitive Drift Rate), and Random Drift. Note that the old Honeywell GG334A gyros were associated with relatively good numbers in the latter two categories. Although its AIDR (bias drift) can be matched or bettered by any of the other five, only the Teledyne SDG-5 has equal or better specifications for ASDR and Random Drift. The Northrup GIG6G comes reasonably close to the Honeywell GG334A in these two categories. Both the Teledyne SDG-5 and the Northrup GIG6G gyros are considered acceptable choices for inertial stabilization control of the SOFIA telescope.

### STABILIZATION LOOP GYROS

	Honeywell GG334A	Honeywell GG1111	Northrup GIG6	Honeywell GG8200	Northrup GIG6G	Teddyne SDG-5*
Type	Gas Bearing Rate Integrating	Ball Bearing Rate Integrating	Ball Bearing Rate Integrating	Gas Bearing Rate Integrating	Gas Bearing Rate Integrating	Dry Tucked Bearing Rate
Deg. of Freedom	1	1	1	1	1	2
Ang. Momentum (gm-cm <sup>2</sup> /Sec)	$2 \times 5^5$	$2.5 \times 10^4$	$3.2 \times 10^4$	$3.2 \times 10^4$	$8 \times 10^4$	$1 \times 10^6$
O.A. Freedom (Degrees)	$\pm 0.5$	$\pm 0.25$	$\pm 14.0$	$\pm 14.0$	$\pm 0.5$	—
Gyro Gain	0.8	0.84	0.7	0.7	$\pm 0.27$	—
Torquer Max Rate (Deg/Sec)	86	90	115	115	50	400
AIDR (Deg/Hr)	$\pm 50$	$\pm 50$	$\pm 15.0$	$\pm 15.0$	$\pm 1.5$	$\pm 2.0$
ASDR (Deg/Hr/g)	$\pm 1.0$	$\pm 15.0$	$\pm 14.2$	$\pm 10.0$	$\pm 2.0$	$\pm 1.0$
Random Drift (Deg/Hr)	$\pm 0.002$	$\pm 0.15$	—	$\pm 0.1$	$\pm 0.003$	$\pm 0.001$
Supp. Electronics	Yes	Yes	Yes	Yes	Yes	Yes
Lead Time (Months)	—	3	3	6-12	6-12	12-24

\*SDG-5 Gyro assemblies use supporting electronics to provide integration.

### Control and Monitoring Systems

The accompanying tabulation is generated primarily to list, for informational purposes, most of the various subsystems envisioned for the total telescope electrical and control system. The requirements for operator manipulation and monitoring of parameters within these subsystems from a main or auxiliary operator's console is indicated to imply the need for front panel space for each of these elements of the system.

### CONTROL AND MONITORING SYSTEMS

	CONTROL SYSTEM TYPE	FRONT PANEL CONTROLS	FRONT PANEL DISP/INDIC
BOUNDARY LAYER FENCE CONTROL	DISP CNTL W/BRAKE	X	X
COARSE TELESCOPE ELEV CONTROL	DISP CNTL W/BRAKE	X	X
APERTURE DOOR	DISP CNTL W/BRAKE	X	X
APERTURE SHIELD	OPEN-CLOSE W/BRAKE	X	X
PRESSURE WINDOW WHEEL	DISP CNTL W/BRAKE	X	X
TELESCOPE AUTO BALANCE	DISP CONTROL	X	X
TELESCOPE SYSTEM ACTV/SHUTDN	DISCRETE LOGIC	X	X
TELESCOPE STABILIZATION	CMPLX FB CNTL	X	X
TARGET ACQ & TRACKING	CMPLX FB CNTL	X	X
CHOPPER DRIVE	CMPLX ANLG/DIG FB	X	X
SECONDARY MIRROR FOCUS	DISP CONTROL	X	X
MECH OFFSET POINTING	DISP CONTROL	X	X
TELESCOPE AUTO CENTERING	ACTIVATION LOGIC	X	X
TELESCOPE CAGING	ACTIVATION LOGIC	X	X
AIR BEARING	ACTIVATION LOGIC	X	X
TELESCOPE ATTITUDE READOUT	ACTIV LGC/ANLG/DIG	X	X
TELESCOPE SYSTEM FAULT ANNUNC	DISCRETE LOGIC	X	X
SYSTEM INTERCOM	AUDIO	X	X
VIDEO DISTRIBUTION	VIDEO SWITCHG	X	
EXPERIMENTER POWER DIST	DISTRIBUTION LOGIC	X	
VACUUM SYSTEM	ACTIVATION LOGIC	X	X
VIBRATION ISOL SYSTEM	COMPLEX FB CNTL	X	X

## Concerns/Risks

It has been shown in the telescope structural design section (4.2) of this Phase A Final Report that the lowest bending mode frequency is about 27 Hz. This analytically determined value is not sufficiently high to meet a rule of thumb which stipulates that the lowest structural mode be at least two octaves above the system bandwidth for a well-behaved typical system. This statement is based on the assumption that a bandwidth of at least 10 Hz will be required of the stabilization loop to properly attenuate the transmitted aircraft vibrations and aerodynamic perturbations. Applying the rule of thumb to the 27 Hz mode, on the other hand, a stabilization system bandwidth of about 7 Hz with well-behaved singularities should be fairly easily attainable; a bandwidth of 10 Hz or greater may be achievable but at the risk of having to accept higher levels of resonant jitter which would compromise the improvement sought by the increase in bandwidth.

Aerodynamic loading, aircraft vibration, and air bearing friction (which includes aircraft quiescent angular excursions) are those outside disturbances to the pointing control system which can greatly influence its final performance. Accurate characterizations of these quantities are not currently available and hence assessments of performance capabilities are tenuous until appropriate tests and measurements can be made. Sizing of the required prime actuators is obviously impacted by the uncertainties of the disturbances; fundamental configuration decisions are also affected by as yet unclear answers to questions such as: whether or not the sizes required are physically and economically practicable; whether or not multiple smaller sized actuator-power amplifier sets need to be the baseline; whether or not other power media should be used (pneumatics, hydraulics), etc. Clearly, boundary conditions for all of the expected disturbances should be ascertained in a timely manner to remove the prevailing uncertainties.

Although it was stated earlier that no active design consideration was given to the use of Image Motion Compensation (IMC) for this Phase A effort, availability in future integration and test phases of a relatively fast and accurate secondary mirror assembly would provide a level of insurance for any shortcoming of the telescope articulating system found at that time. Early scrutiny of the secondary mirror assembly design will thus be necessary to ensure that this back-up philosophy can be implemented to mitigate the concerns relative to the disturbance uncertainties alluded to above. Another IMC option for consideration, if use of the secondary mirror proves infeasible, is an articulating tertiary mirror; this would of course only stabilize the image to the Nasmyth focus.

## **PACS CONCERNS/RISKS**

- **STRUCTURAL MODES**
- **AERODYNAMIC LOADING**
- **AC VIBRATIONS**
- **AIR BEARING FRICTION**
- **TORQUE MOTOR OPTIONS**
- **NEED FOR IMC**

#### 4.5

#### Data Management, Acquisition, and Communications

##### Scope

This section provides a conceptual design for the Data Management, Acquisition and Communication (DMAC) System that is a part of the proposed SOFIA Telescope System. This system includes the hardware and software needed to: acquire the various subsystems' sensor data; process, route and store this data; and provide, for some subsystems, automatic prompts for "go/no-go" commands or corrective command signals for vernier supervisory regulation. The system design is to incorporate major functional blocks of the KAO, including planned upgrades, and incorporating advances in modern communications network technology. As the SOFIA DMAC system is not subject to questions of feasibility, this study is intended only to outline system considerations, develop a conceptual architecture for an efficient, reliable and expandable system, and provide sufficient subelement detail to enable rough costs to be calculated.

## **SCOPE AND GUIDELINES**

### **SCOPE**

- DETERMINE SYSTEM REQUIREMENTS
- DEVELOP CONCEPTUAL SYSTEM ARCHITECTURE
- PROVIDE INPUTS FOR COST ANALYSIS

### **DESIGN GUIDELINES**

- USE KAO AS SYSTEM MODEL
- INCORPORATE PLANNED KAO UPGRADES/MODERN TECHNOLOGY
- INPUT REQUIREMENTS FROM:

KAO SUPPORT CONTRACTORS, KAO OPERATIONS STAFF, AND SOFIA STAFF

## **Major Requirements**

The design concept for the SOFIA Data Management, Acquisition, and Communications System is based on the KAO system, including planned upgrades. Major requirements for the system include high reliability, using proven components and selected redundancy to minimize inflight failures. High noise immunity, including consideration of electromagnetic compatibility and interference minimization, is also needed. Provision for ease of modification by use of standardized hardware and communications protocols is required, to keep the facility up to date and allow for expansion of capability as needed. The communications requirements include direct subsystem-to-subsystem data transfer via a standard local area network, with a "Network Manager" and Test Work Station for network configuring and system diagnostics. A hardware (on-ground) link to a ground-based system simulator is desirable to increase efficiency in configuring the system for the user.

### **MAJOR REQUIREMENTS**

- **RELIABILITY**
  - HIGH MEAN TIME BETWEEN FAILURES
  - HIGH NOISE IMMUNITY
- **REDUNDANCY**
  - BACKUP DATA CPU FULLY AVAILABLE FOR IMMEDIATE SWITCHOVER
  - STAND-ALONE AND NETWORK OPERATION
- **MODIFIABILITY**
  - STANDARDIZATION OF HARDWARE AND COMMUNICATION PROTOCOLS SIMPLIFIES SYSTEM MODIFICATIONS AND SYSTEM EXPANSIONS
  - NETWORK CONCEPT SIMPLIFIES BRINGING UP SYSTEM IN PHASES
- **DATA COMMUNICATIONS**
  - NETWORK CONCEPT ALLOWS DIRECT SUBSYSTEM-TO-SUBSYSTEM DATA COMMUNICATIONS
  - LINK TO GROUND STATION INCREASES EFFICIENCY OF USER CONFIGURATION
  - IMPLEMENTATION OF AN INDUSTRY STANDARD COMMUNICATION NETWORK
  - NETWORK MANAGER AND TEST WORK STATION PROVIDED FOR NETWORK CONFIGURING AND SYSTEM MAINTENANCE

## Design Concept

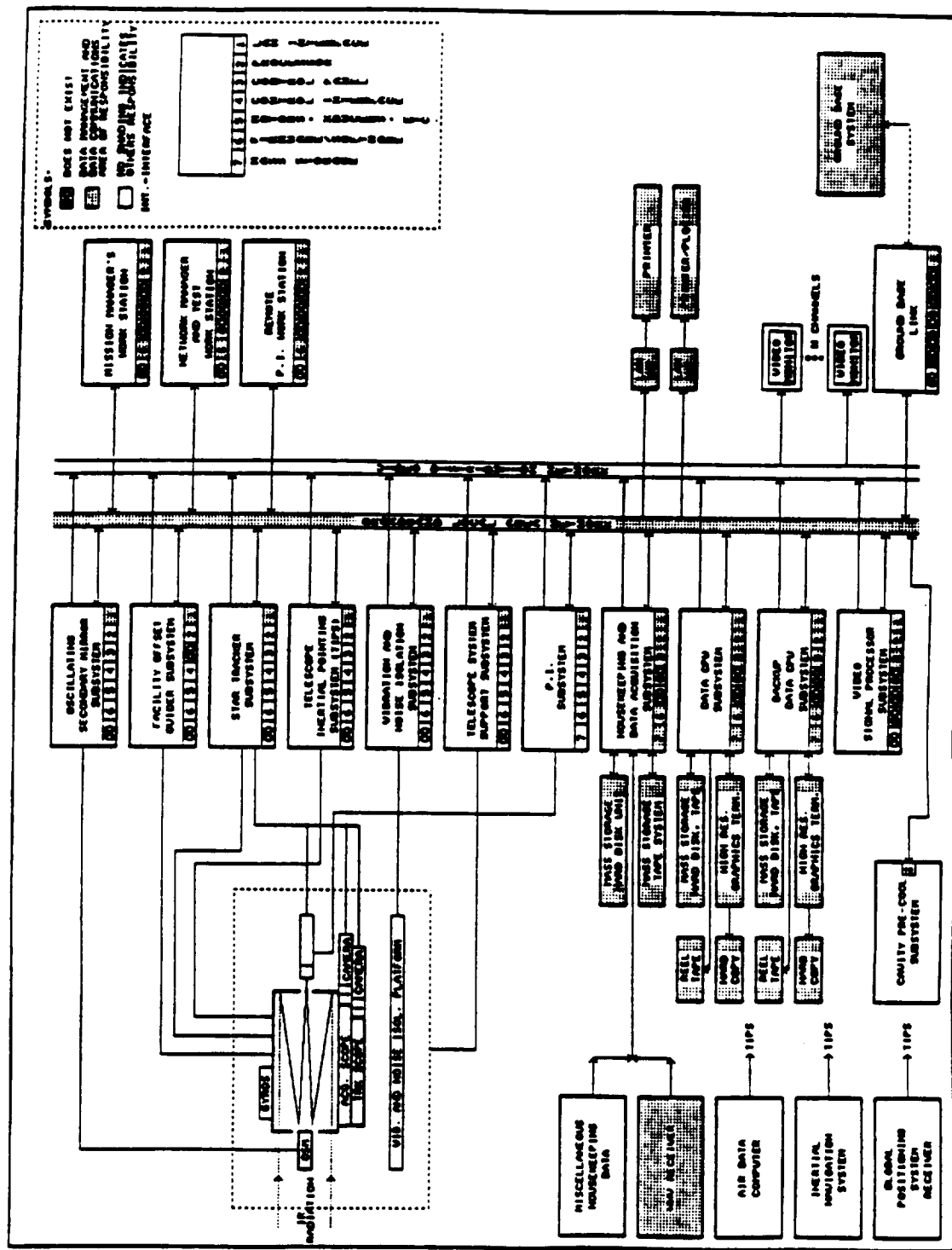
The design approach divides the SOFIA System into major subsystems such as the Oscillating Secondary Mirror, Data CPU, etc. and interconnects these subsystems through a local area network (LAN). Each of the major subsystems consists of from one to seven elements: LAN interface, processor, control panel, control interface, motors/transducers/etc., firmware/software, and/or mass storage. The DMAC provides the LAN interface for all of the major subsystems and only in the case of the House-keeping and Data Acquisition Subsystem, Data CPU Subsystem and its backup, Video Signal Processor Subsystem, Mission Manager's Workstation, Network Manager and Test Workstation, and Remote P. I. Note that the DMAC does not necessarily provide for the functioning of all of the subsystems but only as indicated by the shaded and non-shaded descriptors on the diagram.

## Subsystems

The following is a brief description of each of the subsystems:

1. Oscillating Secondary Mirror Subsystem - This subsystem provides focusing, position angle of chop, offset, amplitude and frequency control to the telescope secondary mirror.
2. Facility Offset Guider Subsystem - This subsystem moves the focal plane camera to enhance the telescope system performance. It uses various parameters, one of which is offset, to position the focal plane camera. It is used in conjunction with the Star Tracker subsystem.
3. Star Tracker Subsystem - This subsystem controls the absolute pointing of the telescope by using the video image from the tracker, acquisition or focal plane telescope and sends corrective azimuth and elevation voltages to the torquer motors.
4. Telescope Inertial Pointing Subsystem - This subsystem monitors the position of the telescope and provides pointing inputs to the positioning system for the location of stars relative to the aircraft. It uses azimuth, elevation, line of sight, and inertial navigation system data such as aircraft position, speed, heading, wind speed and angle, and global positioning data to position the telescope.
5. Vibration and Noise Isolation Subsystem - Subsystem provides telescope isolation from low frequency translational and rotational vibration.
6. Telescope System Support Subsystem - Subsystem provides control for boundary layer fence, aperture door, stator ring, shield, elevation fine balance and azimuth/line-of-sight fine balance.
7. P.I. Subsystem - This subsystem includes the investigator's equipment and also a standard support processor.

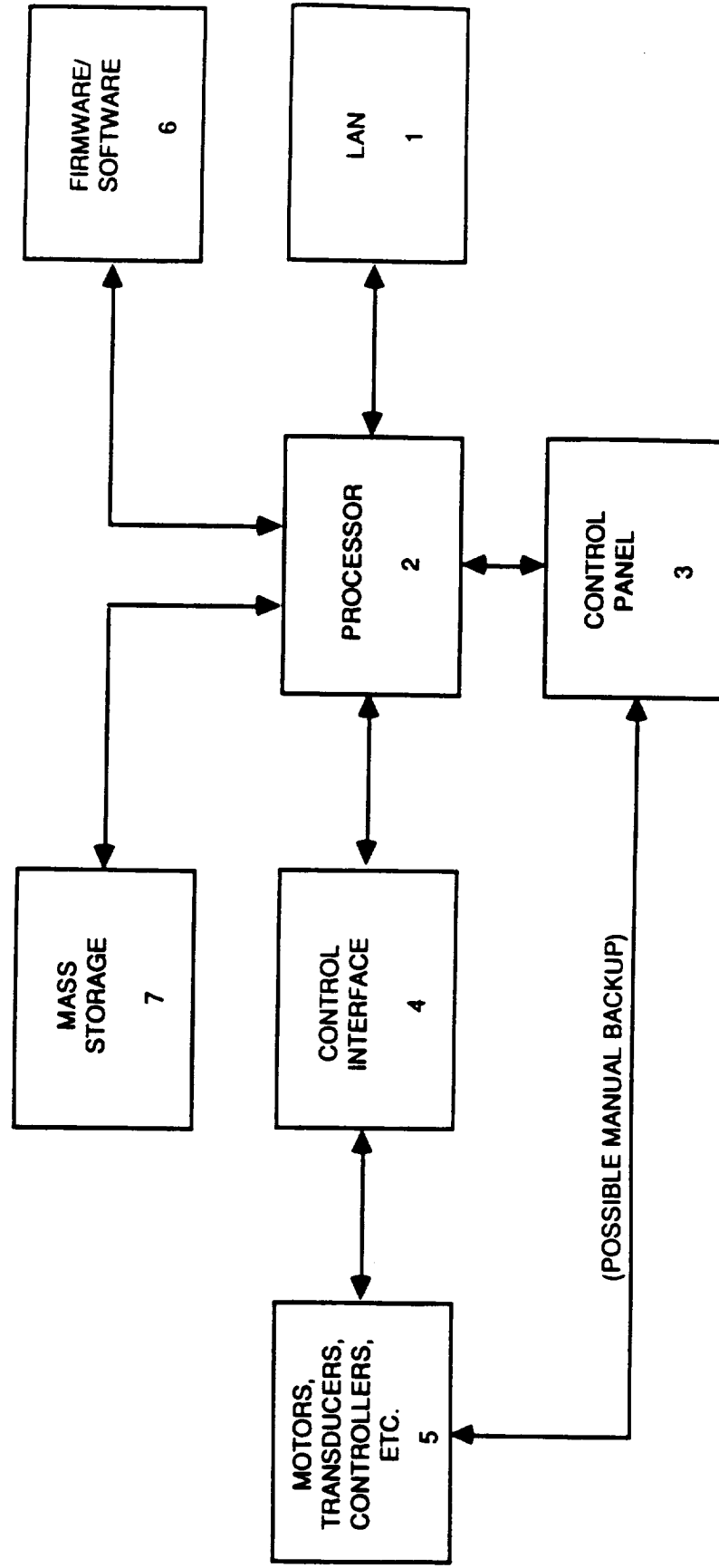
### SYSTEM BLOCK DIAGRAM



## Design Concept (contd)

8. Housekeeping and Data Acquisition Subsystem - This subsystem collects and records housekeeping data and performs utility functions.
9. Data CPU Subsystem - This subsystem collects and records data from the primary experiment. It processes experimental data and supports the principal investigator in the experiment.
10. Backup Data CPU Subsystem - This subsystem provides a full backup to the primary experiment Data CPU Subsystem in the event of a Data CPU failure and hence precludes delay or postponement of the experiment.
11. Video Signal Processor Subsystem - This subsystem provides real time video enhancement.
12. Mission Manager's Workstation - This subsystem provides the Mission Manager with access to log generation software, flight planning and facility monitor and control.
13. Network Manager and Test Workstation - This subsystem provides control, administration, maintenance and testing of the network and each station of the LAN network.
14. Remote P. I. Workstation - This subsystem provides the investigator team with a remote workstation to do offline editing, analysis, etc.
15. Cavity Pre-Cool Subsystem - This subsystem provides pre-cooling to the telescope to reduce the initial temperature differential between the telescope and the observing altitude.
16. Broadband Local Area Network (LAN) - This subsystem provides a standard and flexible network between subsystems via a single coax cable at 10 megabits per second using standard MAP, Manu-"token bus" approach. The MAP LAN architecture is ideal for real time applications and uses the broadband backbone network linking subnets. The subnets provide low-cost networks to localized groups of controllers that are dedicated to specific testing. The broadband backbone uses broadband CATV-like technology, which allows for longer distances between stations and multiple signaling channels.
17. Video Distribution Subsystem - This subsystem provides for the distribution and display of telescope and aircraft data.
18. Miscellaneous Peripheral Equipment - This subsystem is a collection of peripheral equipment. It includes the printer, printer/plotter and WWV receiver.

## SEVEN FUNCTIONAL BLOCKS



#### **Design Concept (contd)**

19. Ground Base System Link - This link allows for communication between the ground base system and the aircraft while on the ground, for example, Ethernet, RS422 or RS485.
20. Ground Base System - This system provides general ground base support for SOFIA, i.e. to develop new software, reduce data from past flights and develop flight plans.

This chart outlines the major elements of each of the subsystems. A bulleted item indicates the element is a part of the design and cost responsibility of the DMAC system. An open circle indicates that the element is outside the area of this system.

## CONCEPT DETAILS

SOFIA											
	<div><div><input checked="" type="radio"/> DMAC Group Task</div><div><input type="radio"/> Other Groups Task</div></div>										
	1	2	3	4	5	6	7	8	9	10	11
	Lead Area Network			Processor		Control Panel		Control Interface		Memory, Keypads, etc.	
	1	2	3	4	5	6	7	8	9	10	11
Oscillating Secondary Mirror Subsystem	●	○	○	○	○	○	○	○	○	○	○
Facility Offset Outer Subsystem	●	○	○	○	○	○	○	○	○	○	○
Star Tracker Subsystem	●	○	○	○	○	○	○	○	○	○	○
Telescope Inertial Pointing Subsystem	●	○	○	○	○	○	○	○	○	○	○
Vibration and Noise Isolation Subsystem	●	○	○	○	○	○	○	○	○	○	○
Telescope System Support Subsystem	●	○	○	○	○	○	○	○	○	○	○
Principal Investigator Subsystem	●	●	○	○	○	○	○	○	○	○	○
Housekeeping & Data Acquisition Subsystem	●	●	○	○	○	○	○	○	○	○	○
Data CPU Subsystem	●	●	○	○	○	○	○	○	○	○	○
Backup Data CPU Subsystem	●	●	○	○	○	○	○	○	○	○	○
Video Signal Processor Subsystem	●	○	○	○	○	○	○	○	○	○	○
Mission Manager's Workstation	●	●	○	○	○	○	○	○	○	○	○
Network Manager & Test Workstation	●	●	○	○	○	○	○	○	○	○	○
Remote Principal Investigator Workstation	●	●	○	○	○	○	○	○	○	○	○
Cooling Pre-Cool Subsystem	●	○	○	○	○	○	○	○	○	○	○
Broadband Local Area Network	○	○	○	○	○	○	○	○	○	○	○
Video distribution Subsystem	○	○	○	○	○	○	○	○	○	○	○
Miscellaneous Peripheral Equipment	●	○	○	○	○	○	○	○	○	○	○
Ground Base System Unit	●	○	○	○	○	○	○	○	○	○	○
Ground Base System	○	○	○	○	○	○	○	○	○	○	○
	see separate description										

## **GROUND BASE SYSTEM**

- AIRCRAFT SYSTEM LINK
- CENTRAL COMPUTER
- MASS STORAGES (HARD DISKS AND TAPE DRIVES)
- TERMINALS
- OPERATING SYSTEM SOFTWARE
- SIMULATOR
- PERSONAL COMPUTERS (IBM OR EQUIVALENT)
- PRINTERS
- PLOTTERS
- LOCAL AREA NETWORK

### **FEASIBILITY ASSESSMENT**

- FOR THE DMAC SYSTEM, PROVEN TECHNOLOGY AND SYSTEM STANDARDS ARE UTILIZED AS MUCH AS PRACTICABLE
- THE CRITICAL SUBSYSTEMS ARE BASED ON SIMILAR SUBSYSTEMS UTILIZED ON THE KUIPER AIRBORNE OBSERVATORY (KAO). OTHER SUBSYSTEMS HAVE BEEN ADDED TO INCREASE EFFICIENCY AND PERFORMANCE, ALL OF WHICH UTILIZE PROVEN TECHNOLOGY
- THROUGH PROPER SELECTION OF THE LAN, CURRENT AND LONG TERM REAL-TIME CONTROL AND DATA COMMUNICATIONS NEEDS CAN BE MET

## SUMMARY

- STANDARDIZATION AND USE OF OFF-THE-SHELF HARDWARE AND SOFTWARE TO REDUCE SYSTEM IMPLEMENTATION, MAINTENANCE, AND COST
- INDUSTRY STANDARD NETWORK (LAN) TO SIMPLIFY SYSTEM COMMUNICATION, MODIFICATION, PROTOCOLS, AND EXPERIMENTER INTERFACE
- BACKUP DATA CPU IS PROVIDED FOR SWITCH OVER, WITH MINIMAL DOWN TIME, TO THE DATA CPU IN THE EVENT OF A FAILURE OF THE DATA CPU
- NETWORK MANAGER AND TEST STATION TO PROVIDE NETWORK MANAGEMENT AS WELL AS OFF-LINE AND ON-LINE SYSTEM MONITORING TO MINIMIZE SYSTEM DOWN TIME

## **OPEN ISSUES AND MAJOR CONCERNS**

### **CONCERNS**

- RECOMMEND THAT STANDARDIZATION OF HARDWARE AND OPERATING SYSTEM BETWEEN SUBSYSTEMS BE CONSIDERED AS A MEANS TO REDUCE COSTS, REDUCE TIME TO IMPLEMENT, AND SIMPLIFY MAINTAINABILITY

#### Telescope and Cavity Thermal Model

A thermal model representing the SOPA telescope and cavity has been developed and analyzed using computer programs TRASYS (Thermal Radiation Analysis System) and SINDA (Systems Improved Numerical Differencing Analyzer). TRASYS was used to generate radiation couplings among all participating surfaces. These couplings, together with other inputs (conduction, convection, and thermal capacitances), are then entered into SINDA to produce steady state and transient temperature distributions. TRASYS was also employed to generate sketches for the model. The thermal model is based on Ames' conceptual structural design, records from the Kuiper Airborne Observatory (KAO), preliminary Computational Fluid Dynamics data provided by the Boeing Co., and other assumed parameters and construction details. The results of the thermal analyses can be used to estimate optical degradation due to air density variation and structural deformation due to uneven thermal expansion.

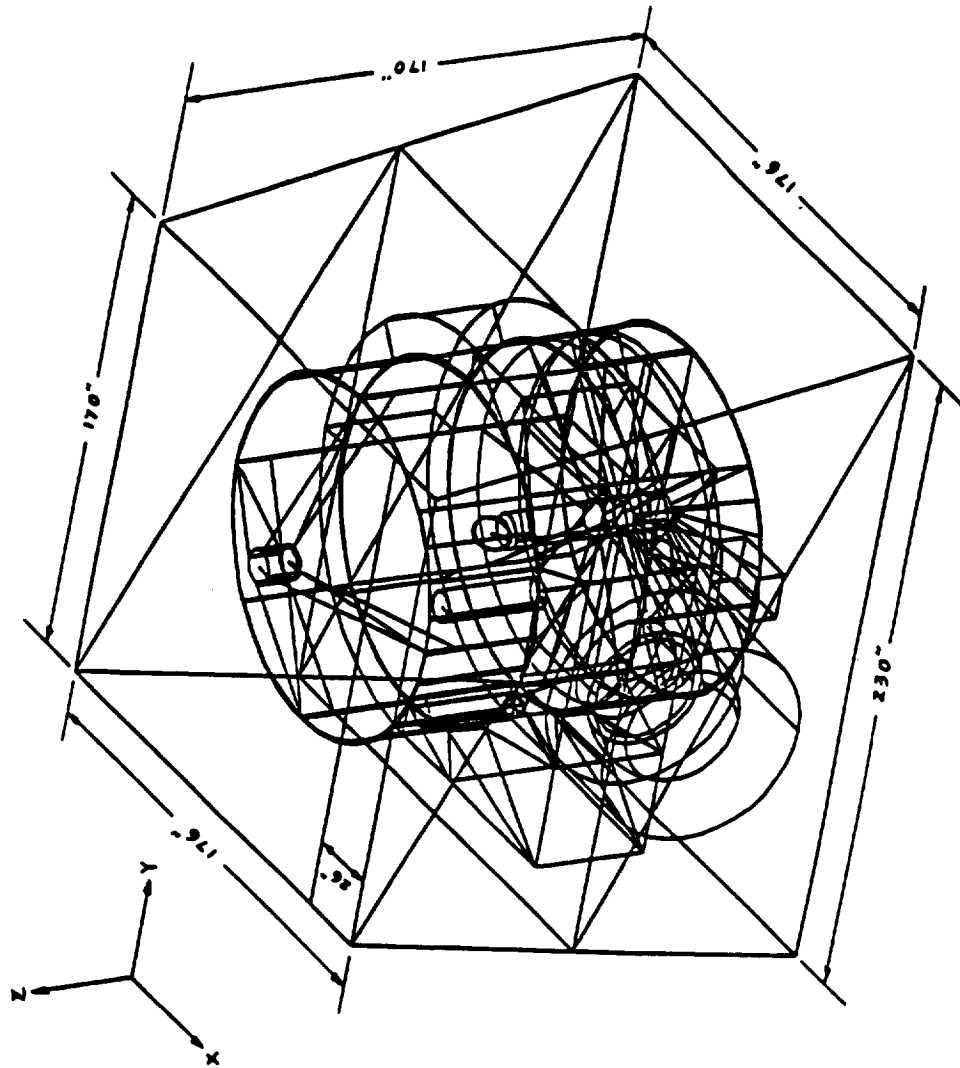
#### The Cavity

The cavity is assumed to be in the shape of a truncated rectangular pyramid. The top of the cavity is open to the sky but is partially covered with the shear layer control "ramp" at the cavity aft bulkhead. All interior surfaces are coated with black paint. The walls have 6" urethane foam insulation between the structural beams and 2" additional flat insulation over the beams.

Due to aerodynamic heating, the air inside the cavity reaches the "recovery" temperature. At an altitude of 40,000 ft and Mach no. of 0.8, the computed recovery temperature is -25 deg. F (free stream air temperature is -70 deg. F).

The telescope and the cavity walls exchange energy with the night sky by radiation. The effective radiation temperature for the atmosphere at 40,000 ft. altitude has been estimated to be -221 deg. F based on reported data on the emissivity of air.

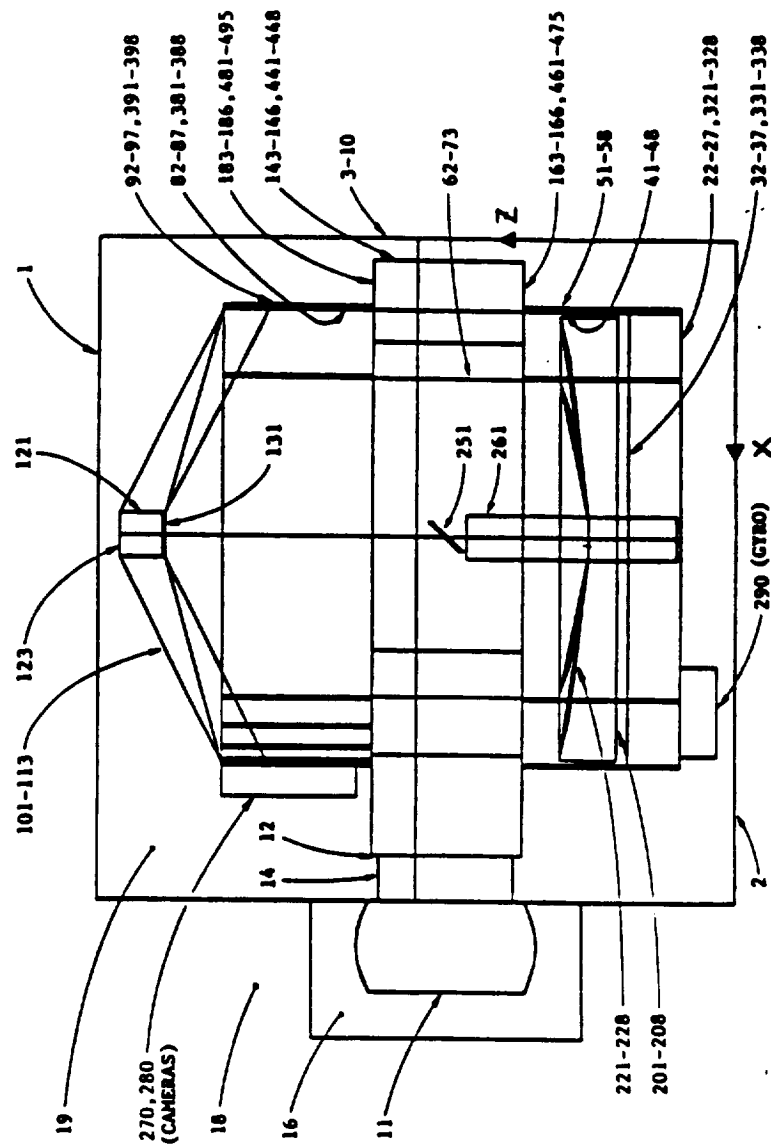
## TELESCOPE AND CAVITY THERMAL MODEL ISOMETRIC VIEW



## The Telescope and Related Equipment

- a. **Metering Tubes:** The upper and lower metering tubes are both fabricated from graphite epoxy/aluminum sandwich material. The face sheets are 1/16" graphite epoxy, and the core material is aluminum honeycomb with a density of 7.9 lb/cu. ft. The overall thickness is 1". Dimensions for the upper tube are 122" dia. x 40" H and for the lower tube are 122" dia. x 42" H.
- b. **Center Piece:** The center piece is constructed from 1/2" thick aluminum plates. It is of rectangular shape on the air bearing side and cylindrical shape on the opposite side. The overall dimension is 156" x 156" x 40".
- c. **Primary Mirror and Mirror Mount:** The primary mirror used in the model is made of Corning's ULE material with 3" x 3" cells, 0.4" top plate, and 0.5" bottom plate. The average thickness of the mirror is 12". The mirror mount has overall dimension of 122" dia. x 14.5" H and is made from 1/2" thick graphite epoxy plates.
- d. **Secondary, Tertiary mirrors and supports:** Secondary and tertiary mirrors are glass mirrors and their supports are made from graphite epoxy.
- e. **Air Bearing:** Material for air bearing and the connecting tube is Invar. Dimensions for the air bearing are 48" dia. x 24" wide and for the connecting tube are 36" dia. x 12" long.
- f. **Nasmyth Chamber:** The modelled Nasmyth chamber is 72" dia. x 72" long and covered with 1" urethane foam insulation.
- g. **Tracker Camera, Acquisition Camera, and Gyroscope:** The cameras are 10" dia. x 36" long and are located on the outside of the upper metering tube. The gyroscope system is a 24" x 16" x 10" are covered with 1/2" thick foam insulation.

## TELESCOPE AND CAVITY THERMAL MODEL X-Z VIEW (WITH NODE NUMBERS)



## Optical Seeing Due to Temperature Variations

If the surface temperature of a solid is different from that of the surrounding air, a convection current is generated which causes a density gradient to exist in the region near the surface. The index of refraction of air is a function of its density as expressed in the Gladstone-Dale Equation:

$$n = \text{index of refraction} = 1 + \delta\rho/\rho_g$$

(1)

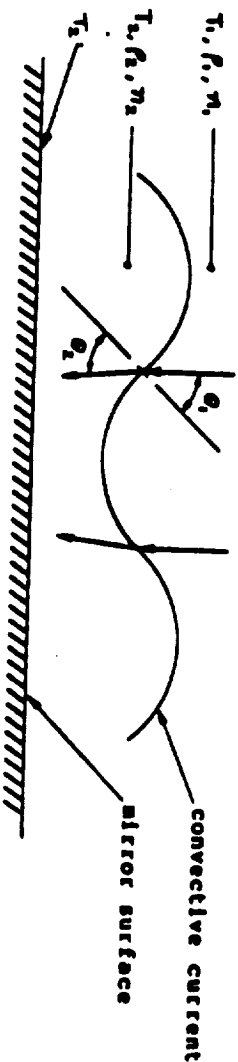
Where

$\delta$  = a constant = 0.000292 for air

$\rho$  = density of air

$\rho_g$  = density of air at standard condition = 0.0807 lb/cu. ft

Consider a simplified model of the convection current as sketched below:



From Snell's law,

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

(2)

At SOFIA's flight condition

$$\rho_1 = 0.016881 \text{ lb/cu.ft}$$

$$T_1 = 435 \text{ deg. R, and}$$

Assuming a temperature difference of 10 deg. K (18 deg. R), then

$$T_2 = 453 \text{ deg. R, and}$$

$$\rho_2 = 0.01621 \text{ lb/cu.ft}$$

Substituting these quantities into eq. (1), we obtain

$$n_1 = 1.000061081 \text{ and } n_2 = 1.000058653$$

Assume  $\theta_1 = 45 \text{ deg.}$  (a typical condition)

$$\theta_2 = 45.00014114 \text{ deg.}$$

Then by eq. (2), The "seeing" angle equals twice the refracted angle, or 1.016 arcsec. Similar calculations show that the seeing angle is 0.52 arcsec for a 5 deg. K temperature difference.

### MATERIAL PROPERTIES

(a) ALL MIRROR SURFACES HAVE EMISSIVITY OF 0.04. ALL OTHER SURFACES ARE ASSUMED TO BE COATED WITH BLACK PAINT WITH EMISSIVITY OF 0.94. THE SKY IS MODELED AS A BLACK BODY AT -221°F.

(b) CONDUCTIVITIES (UNITS IN BTU/HR°F/FT):

ALUMINUM	73 AT -148°F, 92 AT 32°F
INVAR	6.2
GRAPHITE EPOXY	17 (ISOTROPIC)
CORNING'S ULE MATERIAL	0.75
URETHANE FOAM INSULATION	0.023
STAINLESS STEEL (BOLTS)	8.1
FIBERGLASS (THERMAL ISOLATOR)	0.09

(c) SPECIFIC HEAT (UNITS IN BTU/LB°F):

ALUMINUM	0.15 AT -200°F, 0.2 AT 0°F
INVAR	0.11
GRAPHITE EPOXY	0.25
CORNING'S ULE MATERIAL	0.183

### HEAT SOURCES

TRACKER CAMERA	105 W (KAO DATA)
ACQUISITION CAMERA	105 W (KAO DATA)
GYROSCOPE	150 W (KAO DATA)
SECOND MIRROR CHOPPER	50 W (ESTIMATE)
AIR BEARING SUPPLY AIR	15 SCFM (KAO NO. X3)
AIR LEAKAGE FROM CABIN	150 LB/HR (ESTIMATE)

THE CAMERAS AND GYROSCOPE SYSTEM ARE MOUNTED ON THE TELESCOPE. IT IS ASSUMED THAT EACH INSTRUMENT IS FASTENED TO THE TELESCOPE WITH EIGHT STAINLESS STEEL BOLTS (1/4" DIA.). TO REDUCE HEAT TRANSFER, FIBERGLASS SPACERS (1" O.D, 0.3" I.D, 1" LONG) ARE PROVIDED AT EACH BOLTED JOINT.

## Convective Heat Transfer Coefficients

Utilizing Boeing's preliminary Computational Fluid Dynamics (CFD) results, the flow velocities within the cavity have been estimated as follows:

- a. secondary mirror and supporting struts V = 50 ft/sec
- b. upper 1/3 of cavity V = 30 ft/sec
- c. middle 1/3 of cavity V = 20 ft/sec
- d. bottom 1/3 of cavity V = 10 ft/sec

Convective heat transfer coefficients (H) are calculated using the following formulas for boundary layer flow over flat plates:

$$H = 0.664 \times Re^{1/2} \times Pr^{1/3} \times K/L \quad \text{for laminar flow}$$

$$H = 0.037 \times Re^{.8} \times Pr^{.6} \times K/L \quad \text{for turbulent flow}$$

where  $Re$  = Reynolds no. =  $\rho \times V \times L / \mu$

$\rho$  = density = 0.0169 lb/cu.ft

$\mu$  = viscosity = 0.0344 lb/ft/hr

$Pr$  = Prandtl no. = 0.73

$K$  = conductivity = 0.0113 btu/hr/ft/°F

$L$  = length of the plate in the direction of flow, ft

Location	$L$ (ft)	$Re$	Flow Type	$H$ (btu/hr/°F/sq.ft)
a	1	88500	laminar	2.00
b	5	265000	turbulent	1.51
c	10	354000	turbulent	0.95
d	15	265000	turbulent	0.50

Note:

Usually when Reynolds no. is less than 300000, the flow is considered to be laminar. In the cavity of an aircraft, however, due to the existence of substantial pressure fluctuations, the flow is more likely to be turbulent.

In the area between the primary mirror and its support, natural convection is assumed, and the  $H$  value is estimated to be 0.169.

### CAVITY AIR TEMPERATURE

IF THERE IS NO HEAT GAIN OR LOSS IN THE CAVITY, THE AIR TEMPERATURE IN THE CAVITY EQUALS THE RECOVERY TEMPERATURE (-25°F FOR 40,000 FT. AND MACH NO. 0.8). IN THE SOFIA CASE, THE AIR TEMPERATURE CAN BE ESTIMATED BY CONSIDERING AN ENERGY BALANCE FOR THE CAVITY.

#### HEAT FLOWS INTO THE CAVITY (BTU/HR):

THROUGH THE WALLS	4623
THROUGH AIR BEARING	324
AIR SUPPLY TO AIR BEARING	770
POWER TO CHOPPER	171
POWER TO CAMERAS	716
POWER TO GYROSCOPE	512
AIR LEAKAGE THROUGH WALLS	3420
TOTAL	10536

HEAT FLOW FROM CAVITY TO OUTSIDE ATMOSPHERE BY RADIATION = 9280 BTU/HR

NET HEAT FLOW INTO CAVITY AND ABSORBED BY CAVITY AIR = 1256 BTU/HR

MASS FLOW INTO CAVITY FROM THE SHEAR LAYER = 14 LB/SEC

TEMPERATURE RISE OF CAVITY AIR =  $1256 / (14 \times 3600 \times 0.24) = 0.1^\circ\text{F}$

AS SHOWN, THE CAVITY AIR TEMPERATURE RISE IS VERY SMALL AND CAN BE NEGLECTED. THUS, IN ALL THE ANALYSES, THE CAVITY AIR TEMPERATURE IS ASSUMED TO EQUAL THE RECOVERY TEMPERATURE.

### Steady State Results

The steady state solution applies to the case when the telescope and cavity are pre-cooled to near the operating temperature and the aircraft flies at the operating altitude with constant ambient conditions for a period of 2-3 hours. The assumed ambient conditions are:

Altitude = 40000 ft  
Mach No = 0.8  
Free stream air static temperature =  $-70^{\circ}\text{F}$   
Recovery temperature (in the cavity) =  $-25^{\circ}\text{F}$

The calculated steady state temperatures are as follows (in deg. F):

Primary mirror, top	-25.6
Primary mirror, bottom	-23.4 to -25.1
Primary mirror mount, top	-21.9 to -25.2
Primary mirror mount, bottom	-15.0 to -24.9
Lower metering tube	-25.4 to -26.6
Center piece, interior	-27.5 to -30.2
Center piece, exterior	-22.4 to -30.7
Upper metering tube	-25.7 to -29.6
Secondary mirror struts (spider)	-31.3 to -31.5
Secondary mirror assembly	-18.1 to -22.9
Air bearing	+28.7
Air bearing connecting tube	-8.4
Nasmyth chamber	+54.6
Tertiary mirror & supports	-29.3 to -29.8
Tracker camera	+57.4
Acquisition camera	+57.4
Gyroscope System	+79.2
Cavity walls	-15.9 to -31.5

The chart shows steady state temperatures for all the nodes.

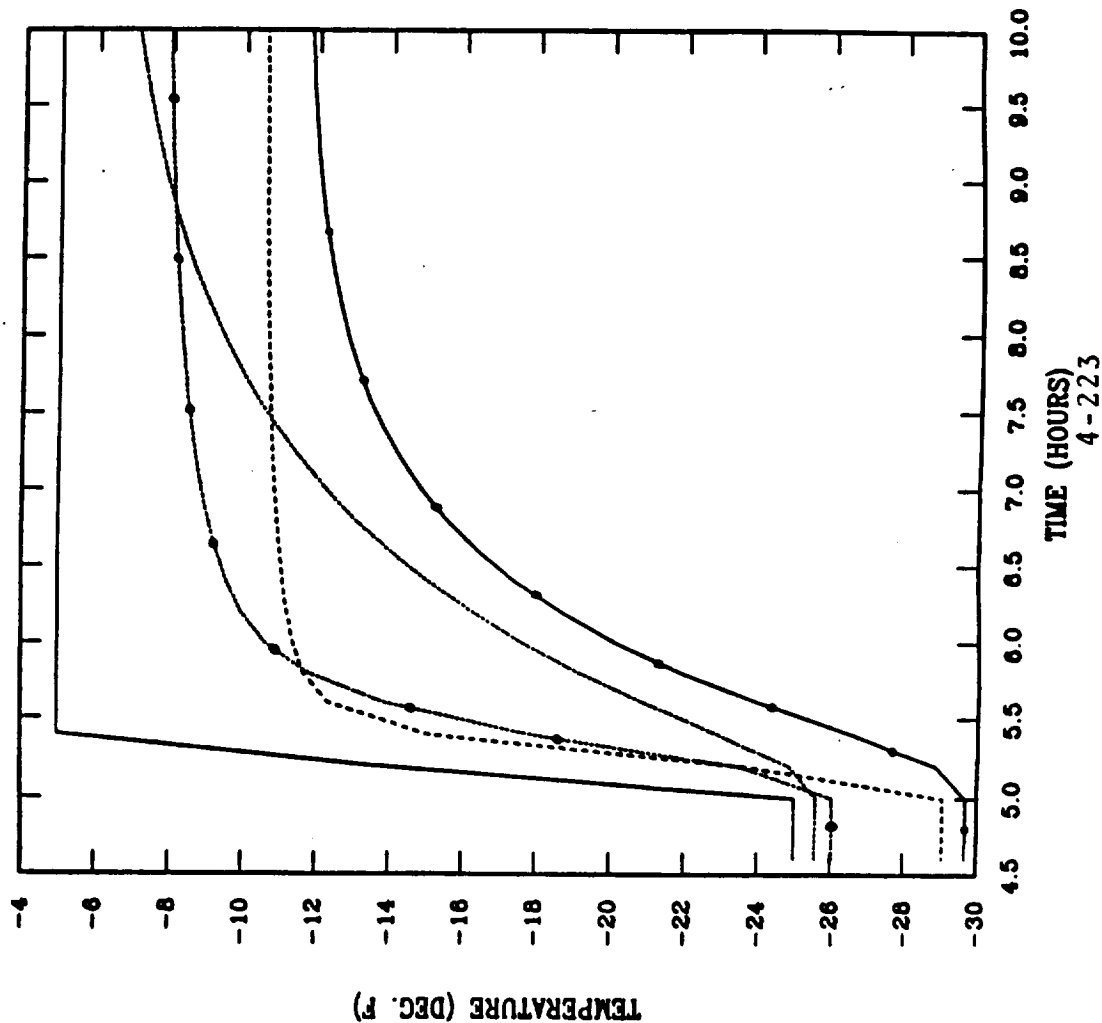
1	-221.00	7	-15.00	7	-31.32
8	-57.66	12	-22.39	13	-8.42
16	-34.55	23	-24.53	23	-24.08
25	-24.08	33	-25.15	34	-25.08
36	-25.14	43	-26.59	44	-25.38
46	-26.55	53	-26.59	53	-25.34
55	-25.33	62	-27.49	63	-29.91
65	-29.90	72	-29.16	73	-29.50
83	-29.01	87	-29.46	93	-29.54
94	-29.16	101	-31.29	105	-31.53
113	-31.51	143	-28.31	149	-27.46
146	-28.22	166	-27.61	183	-29.97
185	-29.04	203	-25.14	204	-25.10
206	-25.13	222	-23.61	223	-28.31
225	-25.59	231	-26.58	232	-25.59
236	-27.78	238	-26.53	241	-28.31
243	-30.37	246	-30.35	247	-30.39
261	-29.76	280	-9.44	281	-29.26
321	-22.93	324	-15.05	325	-18.68
328	-22.95	332	-22.39	336	-21.58
337	-23.02	336	-21.85	335	-22.40
366	-25.93	393	-25.93	384	-27.93
395	-27.79	392	-28.56	393	-27.75
446	-23.59	441	-27.93	442	-27.04
465	-25.10	478	-27.86	461	-25.98
483	-30.68	473	-25.91	475	-30.51
		491	-29.45	493	-30.64
		491	-29.45	493	-30.64

### Transient Analyses

The transient response of the telescope and cavity to a change of ambient condition has been analyzed for two cases. In the first case, it is assumed that the cavity air temperature increases from  $-25^{\circ}\text{F}$  to  $-5^{\circ}\text{F}$  in 20 minutes, and then stays at  $-5^{\circ}\text{F}$  for the remaining time of the flight. In the second case, the cavity air temperature increases from  $-25^{\circ}\text{F}$  to  $-5^{\circ}\text{F}$  in 20 minutes, holds steady at  $-5^{\circ}\text{F}$  for 20 minutes, drops to  $-25^{\circ}\text{F}$  in 20 minutes, then stays constant at  $-25^{\circ}\text{F}$  for the remainder of the flight. The graphs on the next two pages show temperature response for the major components of the telescope. The time constants have been estimated from the case 1 results as follows:

Primary mirror	1.6 hr
Center piece	1.2 hr
Upper metering tube	0.2 hr
Bottom metering tube	0.4 hr
Air bearing	> 10 hr

### TEMPERATURE RESPONSE IN FLIGHT STEP INPUT



## Conclusions for Telescope and Cavity Thermal Analysis

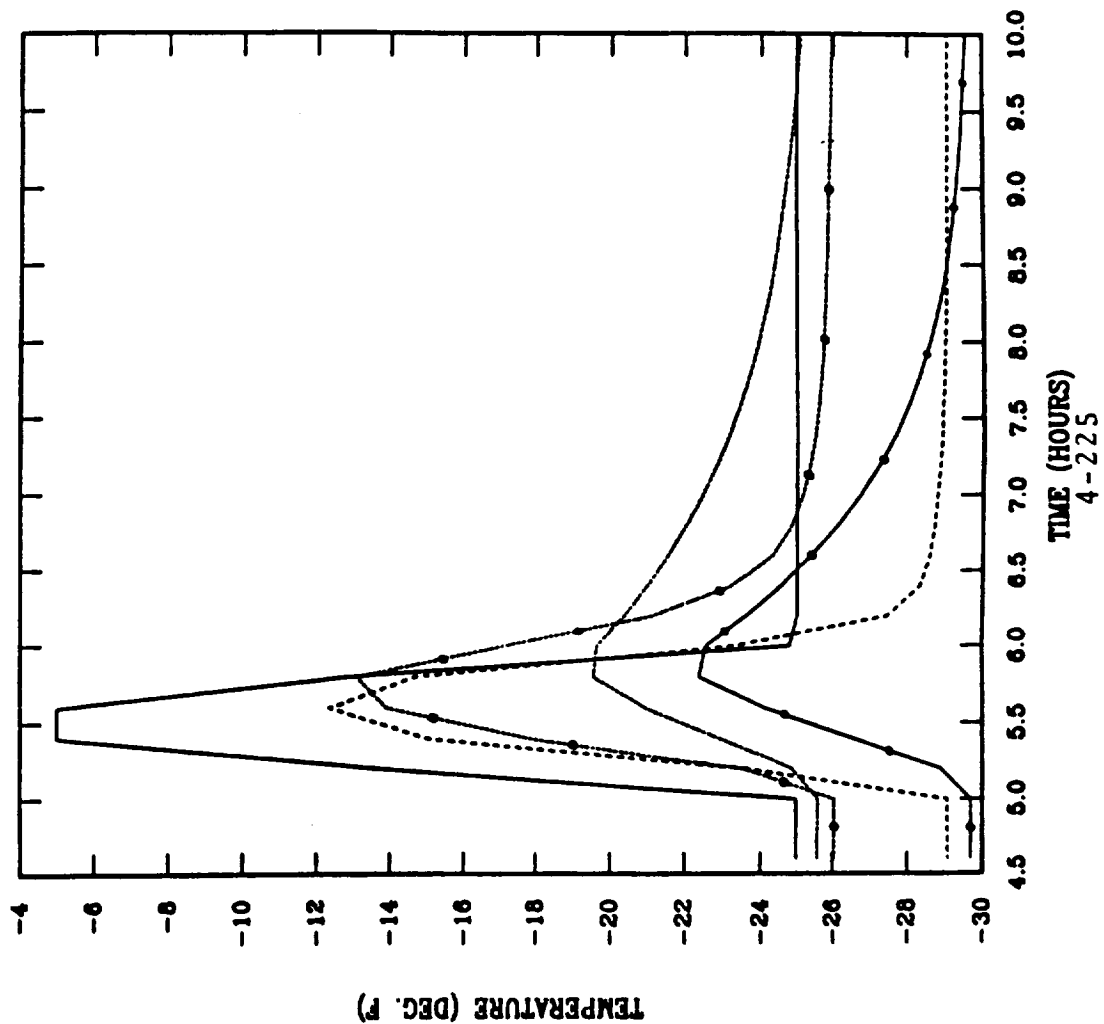
### A. Steady state analysis

1. Radiation is a significant mode of heat transfer and it causes temperature variation of approximately  $6^{\circ}\text{F}$  between the top and the bottom of the telescope.
2. Top surface of the primary mirror has a uniform temperature of  $-25.6^{\circ}\text{F}$ . Since this is very close to the recovery temperature ( $-25^{\circ}\text{F}$ ), little optical "seeing" is expected.
3. Secondary mirror assembly is  $2.1$  to  $6.9$  degrees above the recovery temperature and this can cause a seeing effect of  $0.4$  arcsec. The present analysis assumes a  $50$  W heat dissipation for the chopper. If the true power input is higher, special heat rejection design will be required.
4. Air bearing operates at  $+28.7^{\circ}\text{F}$ , but it is not likely to cause optical seeing since the light path (to Nasmyth instruments) is parallel to the direction of the density gradient. Air bearing does not cause excessive heating of the telescope since the connecting tube is made of Invar which has a low thermal conductivity.
5. Heat sources (tracker camera, acquisition camera, gyroscope) cause temperature variations up to  $15.6^{\circ}\text{F}$  in the telescope structure. If desired, these gradients can be reduced with better thermal isolators.

### B. Transient analysis

1. The transient results show that if the cavity temperature experiences a  $20^{\circ}\text{F}$  temperature change, the top surface of the primary mirror will reach a  $10^{\circ}\text{F}$  approach to the cavity temperature (with an optical seeing effect of  $0.6$  arcsec) in about  $1.2$  hour.
2. For a "ramp" input with temperature change of  $20^{\circ}\text{F}$  and duration of  $20$  minutes, maximum temperature change for the primary mirror is  $5.5^{\circ}\text{F}$  with a seeing effect of  $0.3$  arcsec.

### TEMPERATURE RESPONSE IN FLIGHT RAMP INPUT



### Primary Mirror Cooldown

Before each mission, it is necessary to cool down the telescope and the cavity to near the operating temperature. The primary mirror has relatively high thermal mass and long cooldown time as compared to other components in the system. A thermal model was created to analyze the transient behavior of the primary mirror during cooldown. The model is based on the Corning's ULE design which consists of a 0.4" curved top plate, 0.5" flat bottom plate, and cells of 3"x3" cross section and varying depth between the plates. The cells are separated by 0.075" walls which are called "struts", and strengthened at each corner with 0.15"x0.15" posts. The overall thickness of the mirror varies between 8" at the center and 15.8" at the outer edge. Thermal properties for the ULE material are as follows:

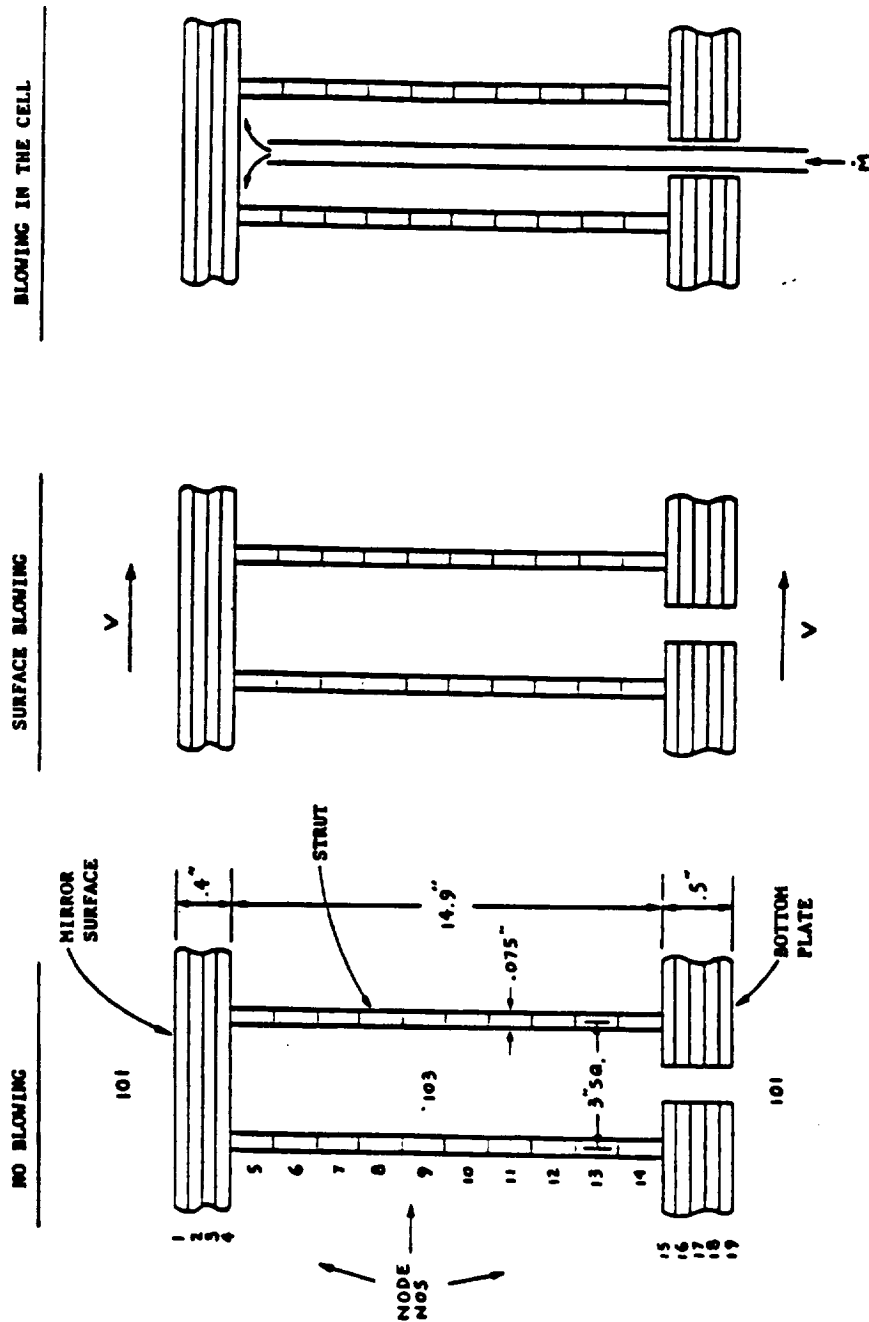
Density	137.9 lb/cu.ft
Conductivity	0.75 btu/hr/ft/°F
Specific heat	0.183 btu/lb/°F

For the present analysis, it is assumed that there are no temperature gradients in the radial and circumferential directions and as a result, a simple model consisting of only one cell was employed (see chart). The mirror is initially at 70 deg. F and, after time=0, it is exposed to gaseous nitrogen at a temperature of -30 deg. F. Conduction, convection, and radiation modes of heat transfer are all present. Radiation couplings among the nodes in the interior of the cell are calculated by the program SSPTA (Simplified Shuttle Payload Thermal Analyzer), and temperature distributions are computed by SINDA (Systems Improved Numerical Differencing Analyzer).

The following methods of cooldown have been studied:

1. Natural convection only.
2. Blowing at top and bottom surfaces.
3. Blowing in the cell.

### PRIMARY MIRROR COOLDOWN



# Heat Transfer Coefficients for Natural Convection

$$H = C \times (Gr \times Pr)^M \times K/L$$

where:

H	=	Heat transfer coefficient, btu/hr-°F-ft-ft
Gr	=	Grashof No. = $g \times L^3 \times \text{Rho}^2 \times (T_w - T_o) / (T_a \times \text{Mu}^2)$
g	=	Acceleration of gravity = 4.17E8 ft/hr-hr
L	=	Length of the plate, ft
Rho	=	Density, lb/cu.ft
T <sub>w</sub>	=	Wall temperature, °F
T <sub>o</sub>	=	Fluid temperature, °F
T <sub>a</sub>	=	Average temperature = $(T_w + T_o)/2$
Mu	=	Viscosity, lb/hr-ft
Pr	=	Prandtl No. = $C_p \times \text{Mu}/K$
C <sub>p</sub>	=	Specific heat = 0.25 btu/lb-°F for nitrogen
K	=	Thermal Conductivity, btu/hr-ft-°F

The values of Rho, Mu, and K are properties of the fluid film and are evaluated at the average temperature T<sub>a</sub>. L equals 4.9 ft for the top and bottom surfaces and 0.244 ft for surfaces inside the cell. The values of C and M depend on the magnitude of Gr x Pr as well as the inclination of the plate, and are expressed as follows:

1. The end plates of the mirror are considered as vertical plates:

$$C = 0.59, M = 1/4$$

$$\text{if } Gr \times Pr < 10E9$$

$$C = 0.13, M = 1/3$$

$$\text{if } Gr \times Pr > 10E9$$

2. For the struts, use average values for vertical and horizontal plates:

$$C = 0.50, M = 1/4$$

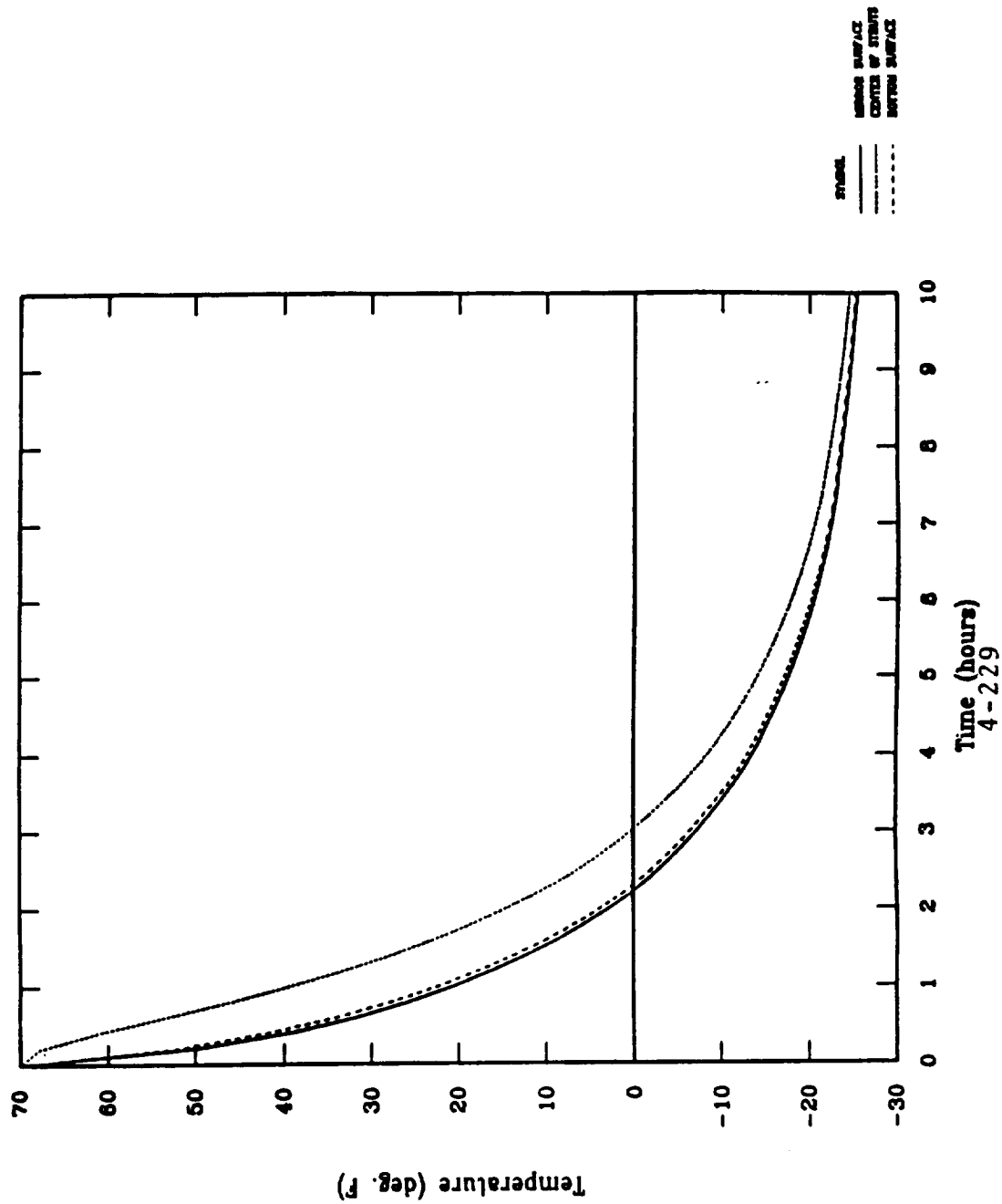
$$\text{if } Gr \times Pr < 10E8$$

$$C = 0.12, M = 1/3$$

$$\text{if } Gr \times Pr > 10E8$$

The above quantities and equations are programmed into SINDA's input and the heat transfer coefficients are evaluated before each iteration.

## PRIMARY MIRROR NATURAL CONVECTION ONLY



## Heat Transfer Coefficients for Forced Convection

### A. Surface blowing

$$H = 0.332 \times Re^{1/2} \times Pr^{1/3} \times K/L$$

if  $Re < 300000$

$$H = 0.0295 \times Re^{.8} \times Pr^{.6} \times K/L$$

if  $Re > 300000$

where

$Re$  = Reynolds no. =  $Rho \times V \times L/Mu$

$V$  = Velocity, ft/sec

$H, Pr, K, L, Rho, Mu$  are as defined in the natural convection section.

### B. Blowing in the cell

For all flow rates considered, the flow in the cell is laminar ( $Re < 2000$ ), and the following formula is applicable (effect of the tube entrance has been neglected):

$$H = 3.66 \times K/L$$

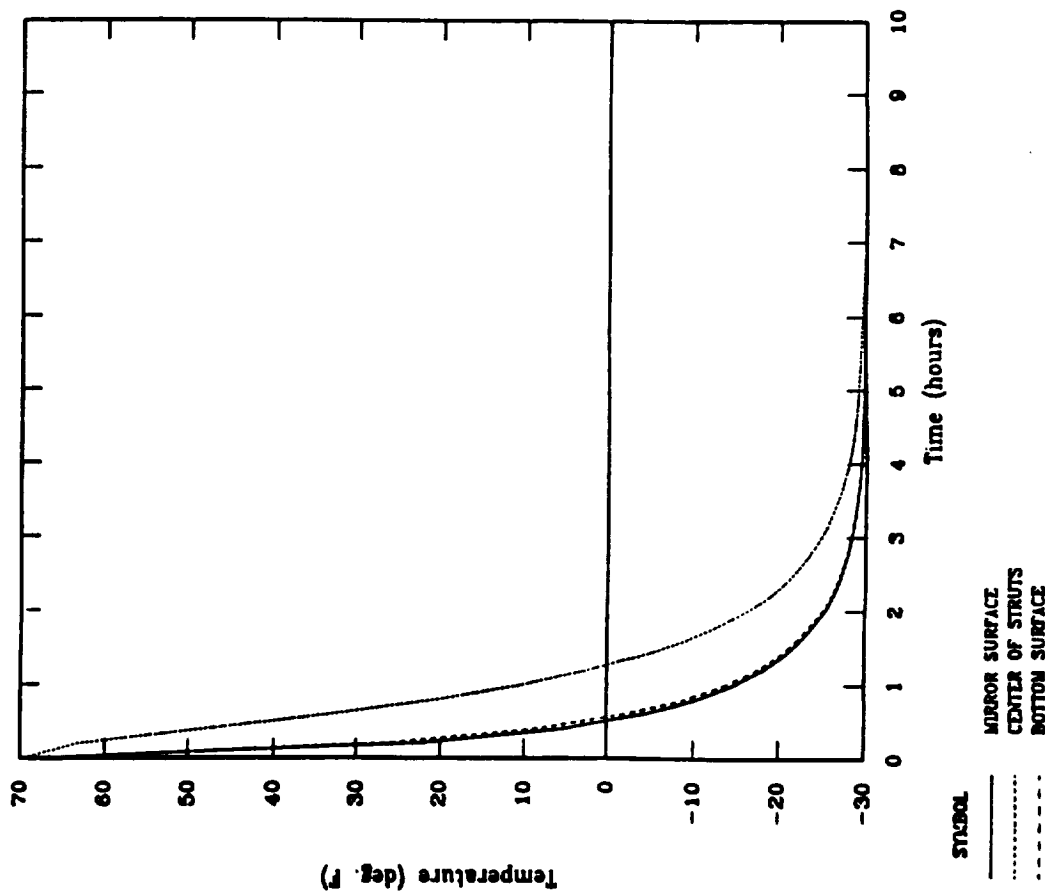
It is noted that the  $H$  value due to forced convection is rather small ( $< 0.2$ ) and therefore natural convection cannot be ignored. Total heat transfer coefficient is the sum of the two coefficients.

## Results of Computation

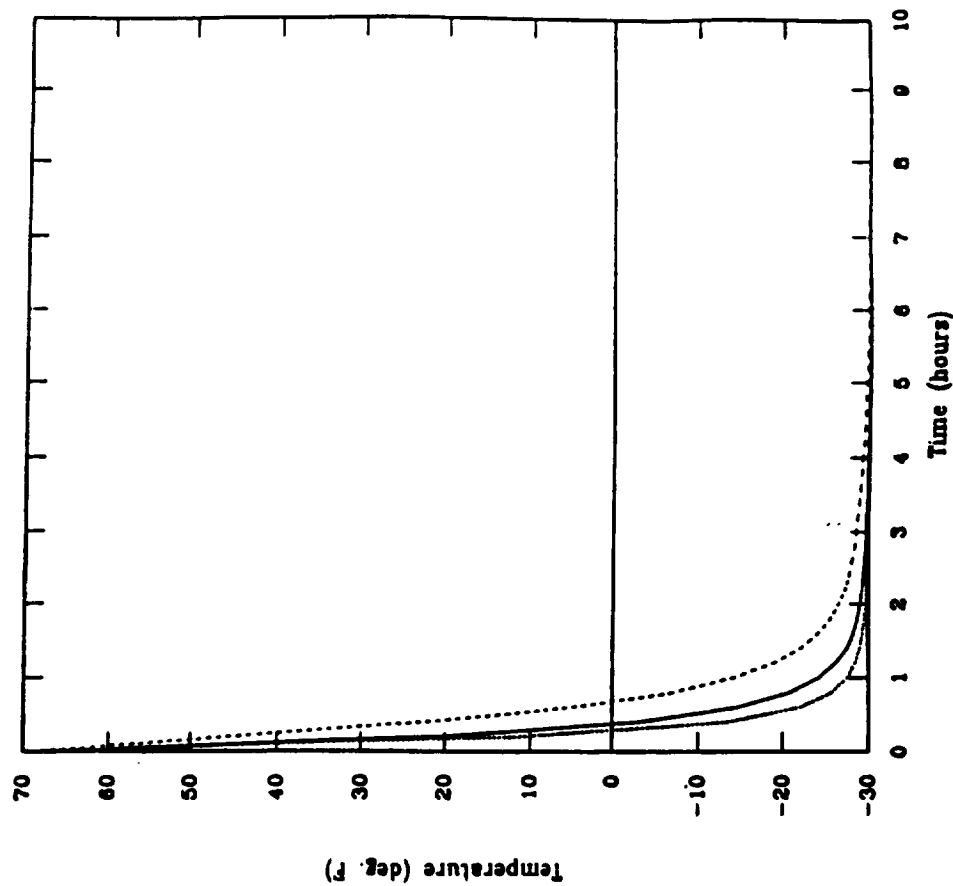
The results of computation are presented as graphs of temperature versus time and time constants. Time constant is defined as the time required to reduce the temperature difference between the solid surface and the fluid to 36.8% of its initial value. Graphs of temperature curves are included for three cases: 1) Natural convection only, 2) Surface blowing at 20 ft/sec., 3) cell blowing at two mirror masses per hour. Time constants have been calculated and tabulated for the above cases and a number of other flow conditions.

### PRIMARY MIRROR

FORCED CONVECTION (20F/S)  
AT TOP AND BOTTOM PLATES



BLOWING IN CELLS  
AT 2 MIRROR MASSES PER HOUR



### Conclusions for Primary Mirror Cooldown Analysis

1. Corning's "ULE" appears to be a desirable material for the primary mirror due to its low thermal mass and coefficient of expansion.
2. The "no blowing" case resulted in fairly high time constant (2.3 hours) and is therefore considered inadequate.
3. Surface blowing at 20 ft/sec reduces the time constant to 1.1 hour and represents an optimum design. Total flow rate requirement for this case has been estimated to be 4000 cu.ft/min.
4. Cell blowing provides faster cooldown with lower flow rates, however, it is not recommended due to the complexity of mechanical design and fabrication (over 1000 tubes are required).

# PRIMARY MIRROR TIME CONSTANT (RESULTS)

## TIME CONSTANTS (HOURS)

CASES	MIRROR SURFACE	STRUT (MIDDLE)	BOTTOM SURFACE
NO BLOWING	1.7	2.3	1.7
BLOWING OVER TOP & BOTTOM SURFACES			
V = 10 FT/S	0.75	1.5	0.78
V = 20 FT/S	0.40	1.1	0.45
V = 30 FT/S	0.25	0.95	0.28
V = 40 FT/S	0.18	0.85	0.18
N <sub>2</sub> BLOWING IN CELL			
1 MIRROR MASS/HR (V = 3.7 FT/MIN)	0.35	0.45	0.80
2 MIRROR MASS/HR	0.35	0.25	0.60
3 MIRROR MASS/HR	0.30	0.20	0.50
4 MIRROR MASS/HR	0.30	0.17	0.50
5 MIRROR MASS/HR	0.30	0.17	0.50

## **Instrument Accommodations**

### **Experimenter Interface: Requirements**

Data collection by the experimenter is paramount, requiring only target acquisition and a chopper reference signal. Though additional computational facilities are available from SOFIA, the observer should be able to conduct his investigation with no more than the minimum support. This mode of operation reduces dependence on the SOFIA system and insures a successful mission.

Archiving of the experimenter's data is provided by a system that accepts either analog or digital data from the experimenter's equipment and records this data along with selected housekeeping data. The archiving system consists of a signal processor and a high speed optical recording system. The experimenter, through his instrument, controls what data is recorded. The design of the system is such that it may function independently and as a stand-alone facility.

Compatibility of the experimenter's system with SOFIA is achieved by using standard serial communications protocol, for example, Ethernet or RS422. Where high speed digital data is to be transferred, a Centronics type interface (8 bit parallel plus strobe) is a leading candidate.

SOFIA system emulation is supported by a series of programs written in "C" that allows the experimenter to use his VMS or Unix system at his facility for system test and verification. Software is also supplied to the experimenter for starfield selection and flight planning.

Observing time is maximized by incorporating computer aided starfield recognition. This is a requirement incorporated within the SOFIA control and data system.

Ease of use is achieved by the use of mouse driven graphics displays of telescope control parameters and responses. The control paths are designed to give the experimenter a high level of command control over the telescope.

## **EXPERIMENTER INTERFACE REQUIREMENTS**

- DATA COLLECTION IS PARAMOUNT
- DATA ARCHIVING FOR LATER ANALYSIS
- COMPATIBILITY TO MINIMIZE SYSTEM INTEGRATION TIME
- SOFIA SYSTEM EMULATION FOR EARLY VERIFICATION
- MAXIMUM OBSERVING TIME
- EASE OF USE

#### Experimenter Interface: Experimenter's Computational Facility

Two computational requirements exist for SOFIA. The facility requires fixed functions of data acquisition, telescope status monitoring, starfield acquisition, telescope control and display. The observer requires functions specific to his experiment as well as a number of fixed functions relating to telescope performance and control.

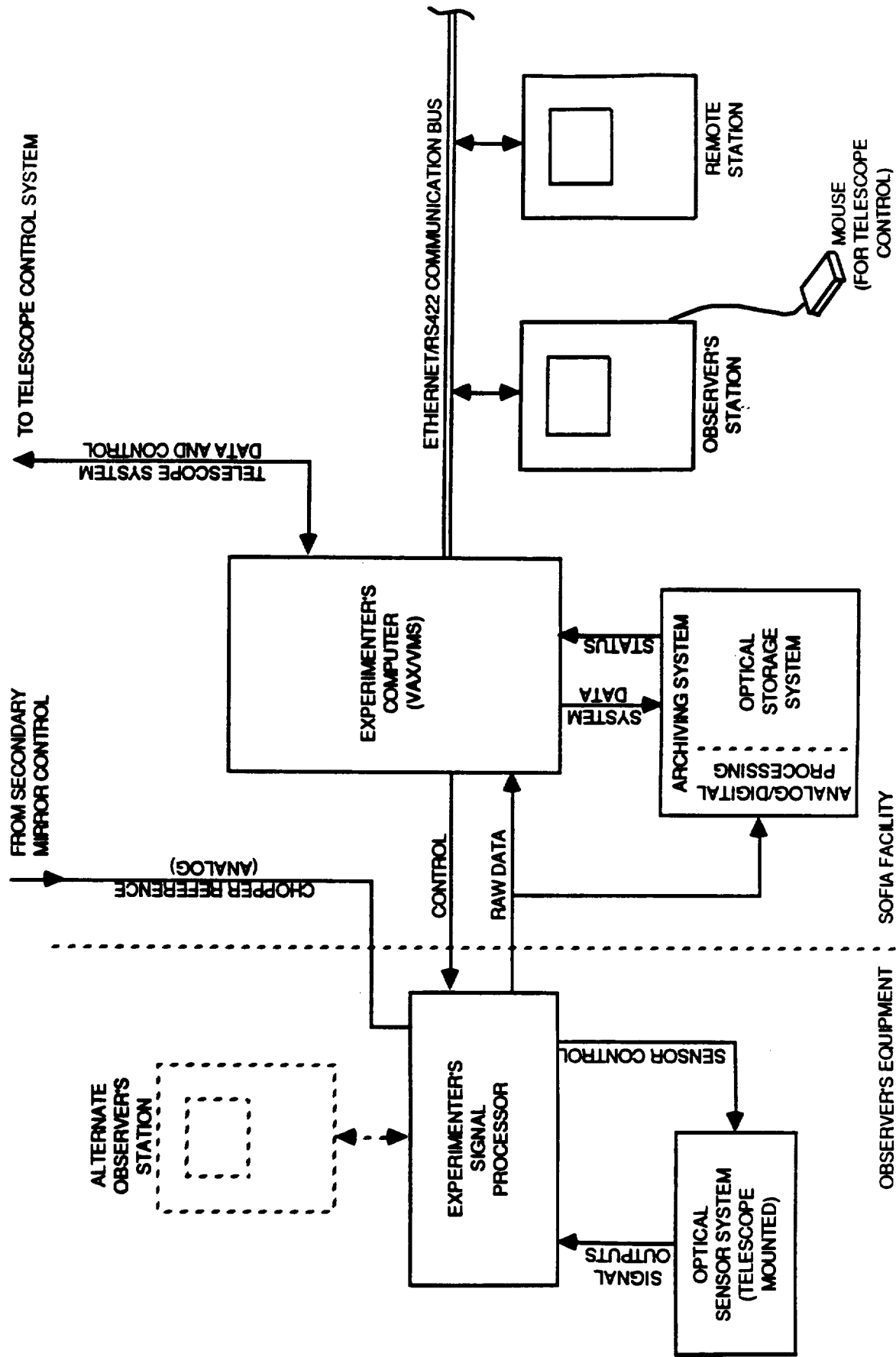
A separate experimenter's computer meets this need by having a fixed interface to the telescope facility while providing flexible interfaces and easily installed computational functions as required by each observer.

The experimenter's computer, for program compatibility, should support the VAX/VMS operating system. For on-line processing it will include floating point processing. Macintosh type computers, using Ethernet or RS 422 protocols will be used for control and display of the experimenter's computer. The terminals, having resident display options, provide a graphical interface for the observer to the telescope system for control and display of data.

In addition to the experimenter's computer, a data archiving facility capable of accepting raw data from the experiments along with selected telescope system parameters is envisioned. This archiving facility will provide the experimenter with a record of all data taken during a flight.

The observer also has the option of making observations without the use of the experimenter's computer by using the alternate station for experiment control.

### EXPERIMENTER'S COMPUTER FACILITY CONCEPT



#### **Experimenter Interface: Display Techniques**

Ideally, the experimenter should be able to control as much of the telescope operation as he wishes. Graphical displays of telescope operation convey the greatest amount of information while allowing a nearly intuitive means for telescope control. This has the advantage of reducing the time the observer requires to learn the operation of the telescope and minimizes the chance for error during an observation.

Heavy emphasis on graphical displays and object oriented programming will insure the greatest compatibility possible between ground based observatories and SOFIA.

Object oriented programming is a departure from past practices but has the advantage of being easy to understand and lends itself to low cost modification of the information presented or the operational routines used during observation.

A hand-drawn diagram of a triangular plot. The plot is bounded by a dashed line labeled "Fence line". A central square contains a small figure. Labels include "S. 1/4 Sec. 10, T. 10 N., R. 10 E." and "S. 1/4 Sec. 11, T. 10 N., R. 10 E.".



## **SECTION 5**

### **AIRCRAFT SYSTEM DESCRIPTION**

- 5.1 Introduction**
- 5.2 Aircraft System Requirements Summary**
- 5.3 Aircraft and Cavity Modification Concept**
- 5.4 Cavity Environmental Control**
- 5.5 Aircraft Interfaces**
- 5.6 Conclusions and Major Issues**

## Introduction

### Background

In 1986, NASA/Ames Research Center (ARC) initiated studies into the feasibility, preliminary concepts, and costs for development of a three-meter class airborne infrared observatory, which is intended to improve astronomy data gathering capability beyond that currently available with the 0.91 meter telescope in the KAO. An early in-house assessment of existing airborne platforms established that only certain models of the Boeing 747 would provide the altitude, endurance and fuselage volume capabilities necessary to meet the established requirements for SOFIA. Consequently, a two-phase concept definition study was implemented under contract with the Boeing Military Airplane Company (BMAC) to develop concepts for aircraft modification, determine aircraft performance capabilities, and estimate costs for the SOFIA Aircraft System. A major Phase I BMAC effort concentrated on the required aircraft modifications for different telescope (primary mirror) diameters, in the range of 2.5-3.5 meters, assuming an  $f/1$  primary mirror to size the telescope length. Having established the 747SP model as the most suitable platform, BMAC showed in Phase I that a 3m system was the upper limit of telescope size which would fit within the existing fuselage/main deck floor volume; cost was shown to be prohibitive to modify any of these existing structures (i.e., "bulge" the fuselage and lower the floor) to accommodate telescopes greater than 3 meters. Preliminary concepts and ROM costs were developed for the various alternatives during Phase I. Subsequently, in the Phase II aircraft modification study, the trade space was narrowed so that the BMAC effort concentrated on more detailed analyses, concept refinement, and updated costs for a baseline 3 meter telescope, with preliminary external dimensions and requirements provided by ARC. The objectives, requirements, concept definition, top-level interfaces, design drivers, and major issues developed by BMAC during the Phase II study are described in this section. More details of their study results, including component drawings, are available in the BMAC Phase II Final Technical Report.

### **AIRCRAFT MODIFICATION STUDIES BACKGROUND**

- NASA/ARC INITIATED TELESCOPE SYSTEM AND AIRCRAFT MODIFICATION STUDIES FOR SOFIA, 1986
- BOEING 747 ESTABLISHED AS ONLY AIRCRAFT TYPE CAPABLE OF MEETING ALL REQUIREMENTS
- BOEING MILITARY AIRPLANE COMPANY AWARDED 2-PHASE CONTRACT TO STUDY AIRCRAFT MODIFICATION, PERFORMANCE, AND COST
- PHASE I STUDY ESTABLISHED UPPER LIMIT TO TELESCOPE SIZE FOR A PROGRAM OF REASONABLE COST
- PHASE II STUDY (COMPLETED AUGUST 1987) REFINED CONCEPT, PERFORMANCE, AND COSTS ASSOCIATED WITH A 3-METER F/1 TELESCOPE IN A BOEING 747SP

## **Study Objectives**

The primary goal of the contracted Phase A aircraft modification system level studies was to establish the feasibility of installing a large (3 meter class) telescope in a wide body aircraft (Boeing-747SP) to provide an airborne platform for infrared astronomy. The Phase I study objectives were: development of a conceptual configuration that is not cost prohibitive, yet satisfies system level requirements; preparation of a preliminary ROM cost estimate and program schedule for subsequent aircraft modification and mission equipment installation; and identification of issues and technical problems that appear to have significant cost, schedule, or performance impact. The Phase II study was intended to refine the selected Phase I concept and further develop it into a more mature concept, including preliminary system performance requirements. The Phase II objectives were: determine key aircraft/subsystem requirements for incorporation into the NASA SOFIA requirements document (PD-2000); estimate the drag increment for the baseline Phase II aero-optics (boundary layer control (BLC)) interface configuration; develop stress data and analyses to validate the structural modification concept; develop and refine the Phase II conceptual configuration based on the established requirements; establish requirements sensitivity for identified "design drivers"; and develop a cost/schedule for the updated configuration, with increased visibility (i.e., breakdown) to improve confidence in the cost estimate.

## **PHASE II STUDY OBJECTIVES**

- ESTABLISH AND DOCUMENT PRIMARY AIRCRAFT/SUBSYSTEM REQUIREMENTS (WITH ARC)
- DETERMINE DRAG/PERFORMANCE PENALTY OF CAVITY AND BLC CONCEPTS
- DEVELOP STRESS DATA AND ANALYSES TO VALIDATE STRUCTURAL MODIFICATION CONCEPT
- REFINE MODIFICATION CONFIGURATION CONCEPT
  - 3.0 METER TELESCOPE (PRIMARY DIAMETER)
  - 20°-60° ELEVATION FIELD OF VIEW - UNVIGNETTED
  - POROUS FENCE AND AFT RAMP FOR BLC
  - AFT BULKHEAD/RAMP/DOOR CONFIGURATION DETAILS
  - DOORS AND FENCE THAT TRACK TELESCOPE MOTION
  - THERMAL AND ACOUSTIC ISOLATION CONCEPTS
  - UPDATE "LOPA" AND WEIGHT AND BALANCE
  - IDENTIFY SPECIALIZED GROUND SUPPORT EQUIPMENT
  - IDENTIFY INTERFACES/ACCOMMODATIONS
- ESTABLISH REQUIREMENTS SENSITIVITY
- DEVELOP COST/SCHEDULE FOR REFINED CONCEPT

### Aircraft System Requirements Summary

The SOFIA Aircraft System requirements fall into three basic categories: aircraft performance capabilities; mission equipment, crew and other accommodations; and the cavity modification. The modified aircraft performance requirements for a science mission payload include maximum time to climb to FL410, minimum endurance at that altitude in observing configuration, and platform attitude accuracy and stability while observing. For deployment or ferry missions, a minimum aircraft range is established with door closed and carrying the crew and support equipment needed for remote operations.

Aircraft accommodations for science mission equipment and crew include equipment (consoles, racks) mounting provisions, cabin environment limits, communications interfaces, cable routing accommodations, safety/emergency equipment provisions, electrical power interfaces, passenger seating, galley/lavatory provisions, etc. Other accommodations include provision of fuselage ports for water vapor (atmospheric overburden) monitors, and aft mounting for air compressors, vacuum pumps and nitrogen tanks with associated line routing to the cavity, V.I.S./air bearing or science instrument. A communications interface between the mission computer (CPU) and the aircraft autopilot is needed to enable remote aircraft steering commands, to keep the telescope within its motion envelope while tracking celestial objects. Also, data from the aircraft's air data computer (e.g., speed, altitude, wind vector) is routed to the mission computer for archiving. Detailed requirements for these accommodations are delineated in the "SOFIA and Related Requirements" specification (PD-2000), and in the Statement of Work specifications for the BMAC aircraft modification study contract.

### **SUMMARY OF AIRCRAFT SYSTEM REQUIREMENTS**

- AIRCRAFT PERFORMANCE
  - CLIMB TO FL410, EST. CRUISE CONDITIONS, AND OPEN DOOR WITHIN 30 MINUTES
  - MAINTAIN ALTITUDE  $\geq$  FL410 FOR AT LEAST 6.5 HOURS WITH DOOR AND BLC FENCE OPEN
  - DEPLOYMENT MISSION:  $\geq$  6000 N.M. RANGE WITH IFR RESERVES (DOOR CLOSED)
  - ATTITUDE ACCURACY/STABILITY:  $\leq \pm 0.5^\circ$  RMS AZIMUTH, ROLL AND PITCH AXIS
- MISSION EQUIPMENT/CREW ACCOMMODATIONS
  - EQUIPMENT MOUNTING PROVISIONS (CONSOLES, RACKS, ETC.), TO WITHSTAND EMERGENCY/CRASH LOADS
  - CABIN TEMPERATURE, PRESSURE, HUMIDITY, AND SOUND LEVEL LIMITS
  - PROVISIONS FOR SAFETY EQUIPMENT AND ANNUNCIATORS, GALLEY, AND LAVATORIES
  - PROVISIONS FOR COMMUNICATIONS (INTERPHONE) AND ELECTRICAL POWER INTERFACES
  - INSTALLATION ACCOMMODATIONS FOR POWER AND COMMUNICATIONS CABLES
  - PROVISION OF ADDITIONAL SEATING FOR FERRY PASSENGERS
  - PROVISION OF PORT(S) FOR WATER VAPOR MONITOR(S)
  - ACCOMMODATE AIR COMPRESSORS, VACUUM PUMPS, AND NITROGEN TANKS WITH LINE ROUTING
  - PROVIDE SIGNAL INTERFACE BETWEEN AUTOPILOT/AIR DATA COMPUTER AND MISSION CPU

#### Aircraft System Requirements Summary (Contd)

The chart summarizes requirements levied on the aircraft cavity modification for Telescope System accommodations. First, the cavity geometry must allow sufficient "dynamic envelope" for the ~ 3 meter telescope with its required motions, including elevation range, cross-elevation range, and vibration isolation system travel; cavity devices must be located accordingly. A preliminary limit on the cavity structure mass (i.e., above a standard configuration aircraft) has been established to allow sufficient aircraft performance capability. (To the extent that the cavity, telescope, and mission equipment/payload masses increase beyond current goals, engine performance enhancement will be needed to meet the aircraft performance requirements; drag increase is also a factor). In order to minimize cavity convection and radiation due to temperature differences across the bulkheads, a maximum thermal transfer goal of 2000W has been established; convection currents contribute directly to "seeing" image degradation, and radiation (i.e., hot surfaces) may add noise to the IR signal.

The cavity opening dimensions are established, given the telescope size and motion range, to preclude vignetting of the image at motion extremes. The two-section door must reduce this opening by following telescope elevation motion, in order to reduce drag; it must be fully operable on the ground and in-flight and must open the required amount within 3 minutes. For control of the shear layer (to minimize "seeing" effects) a segmented fence mounted on the fuselage forward of the cavity, and an aft bulkhead mounted passive "ramp" are the current baseline; the fence segments will deploy and retract to follow the door and telescope motion, to minimize drag. Future wind tunnel testing results may modify the shear layer control concept.

Several additional cavity requirements relate to accommodating equipment routing and access provisions between the cabin and the cavity. For instance, power/communications cables and pneumatic lines will have to traverse the bulkhead interface, requiring feedthrough provisions. Additionally, ground access to the cavity (e.g., for instrument mounting at Cassegrain location) must be accommodated; a door in the forward bulkhead is to be provided for this purpose. The forward bulkhead is also required to house the telescope capture/locking device. The aft bulkhead must accommodate the vibration isolation system mounts and leave a circular cutout for insertion of the air bearing with its pressure seal; it also will have an observation window to allow inflight monitoring of the telescope and cavity systems. Finally, a range of interfaces must be provided for the cavity environmental control systems, including ducts/ports for the ground-based cooling system, the aircraft nitrogen purge/dehumidification/cooling system, and the aircraft cavity heating system. These provisions are depicted in several of the figures which follow.

### SUMMARY OF AIRCRAFT SYSTEM REQUIREMENTS (CONTD)

- AIRCRAFT CAVITY SUBSYSTEM
  - VOLUME: ACCOMMODATE 156" DIA. x 151" L. TELESCOPE WITH +20-60° UNVIGNETTED ELEVATION RANGE AND  $\pm 2^\circ$  (TBD) LOS/AZMUTH RANGE, WITHOUT INTERFERENCE
  - MASS: CAVITY MOD. WEIGHT  $\leq 16,000$  LBS (ABOVE STANDARD CONFIGURATION)
  - THERMAL ISOLATION: CABIN/CAVITY THERMAL TRANSFER  $\leq 2000$  W (GOAL, AT ALTITUDE)
  - CAVITY OPENING: 146" x 210" (FULLY OPEN; CONSISTENT WITH MOTION REQUIREMENTS)
  - CAVITY DOOR: DEPLOYABLE/RETRACTABLE IN-FLIGHT AND ON GROUND  
OPENING TIME  $\leq 3$  MINUTES  
DOOR OPENING TO TRACK TELESCOPE ELEVATION (I.E., 2-PIECE DOOR)
  - SHEAR LAYER CONTROL: BLC FENCE AND AFT RAMP; FENCE TO TRACK TELESCOPE ELEVATION
  - FEEDTHROUGHS: AFT BULKHEAD PROVISIONS FOR CABLE/PNEUMATIC LINE FEEDTHROUGHS
  - ENVIRONMENTAL: ACCOMMODATE GROUND AND AIRBORNE CAVITY COOLING/DEHUMIDIFICATION/  
HEATING INTERFACES
  - BULKHEADS: ACCOMMODATE VIBRATION ISOLATION SYSTEM MOUNT, AIR BEARING  
"HOLE" AND WINDOWS ON AFT BULKHEAD;  
PROVIDE ACCESS DOOR AND TELESCOPE LOCKING DEVICE ON FORWARD BULKHEAD

### 5.3

#### Aircraft and Cavity Modification Concept

##### Aircraft Concept

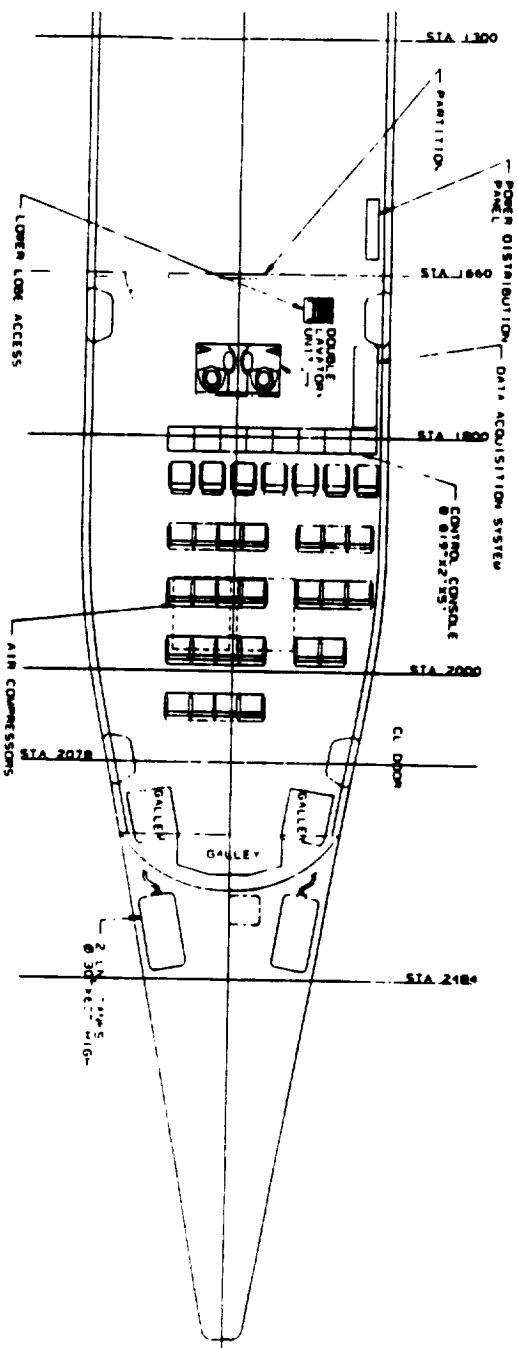
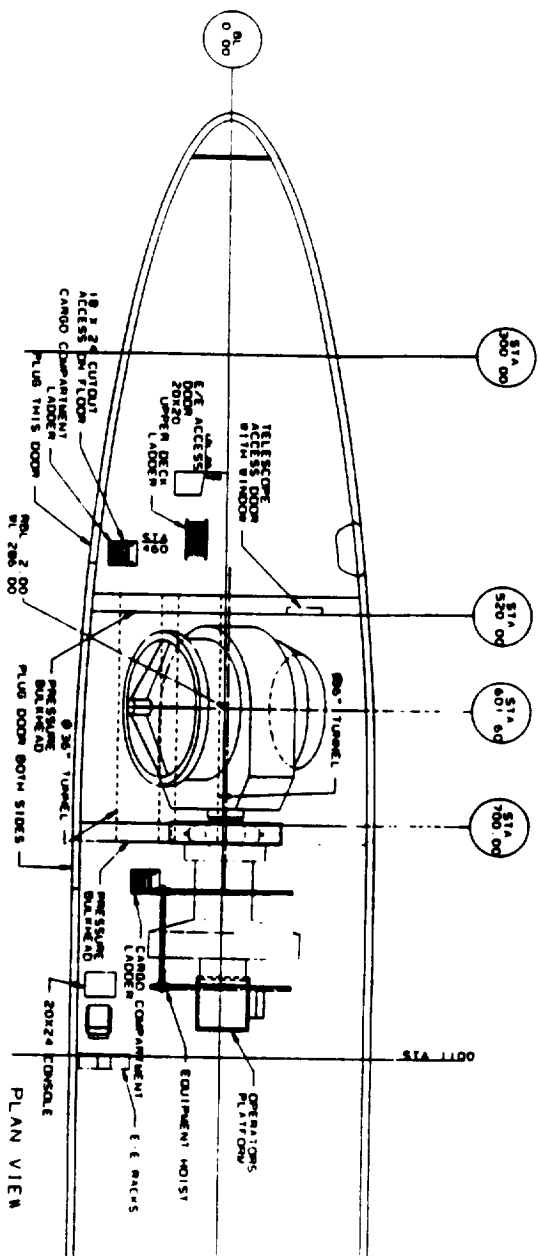
The following charts detail the BMAC Phase A concept for the SOFIA platform, for which a Boeing 747-SP is baselined. As shown, the 3-meter telescope is installed in a cavity forward of the wing, where the fuselage cross-section is greatest. Two full-depth pressure bulkheads separate the cavity from the fore and aft cabins; the aft bulkhead supports the entire Telescope System weight via the bulkhead-mounted vibration isolation system. Two pressurized 36-inch diameter tunnels connect the two cabins under the cavity floor (unpressurized area); one tunnel is used for personnel transfer with a "cart" and the other is for equipment systems routing (wiring, tubing, etc.). Ladders and access doors are provided in both cabin floors for access to the under-floor tunnel exits.

An equipment hoist is provided above the instrument mount/counterweight to assist in instrument handling. An "operation platform" is shown aft of the instrument mount allowing inflight and ground access to the Nasmyth instrument. One experimenter position is located beside the counterweight, with a console, seat and equipment rack.

The remainder of the mission consoles, seats and racks are located in the aft aircraft section behind a noise-attenuating partition. This location provides a quieter environment and assists in aircraft c.g. balancing. Lavatories and galleys are located in the aft compartment. The air compressors (for air bearing and vibration isolation system) are shown in the aft cargo compartment, and the  $LN_2$  tanks for cavity dehumidification/cooldown are located in the unpressurized tail area. Five passenger doors remain "unplugged", four in the aft section and one forward of the cavity. The cargo compartment is accessible through the standard external cargo door and a cabin floor mounted hatch and ladder. A power distribution panel is located forward of the cabin partition, near a 4-inch diameter upper fuselage hole for installation of a water vapor monitor.

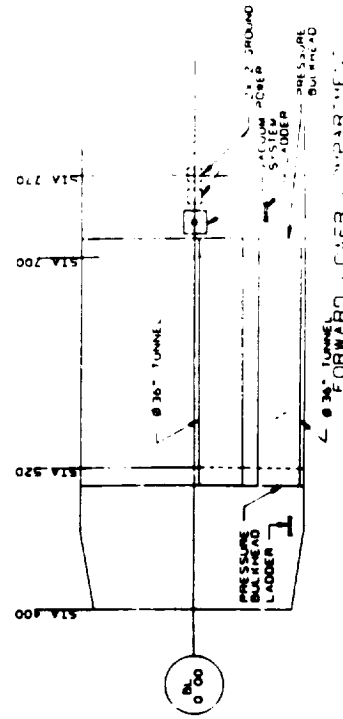
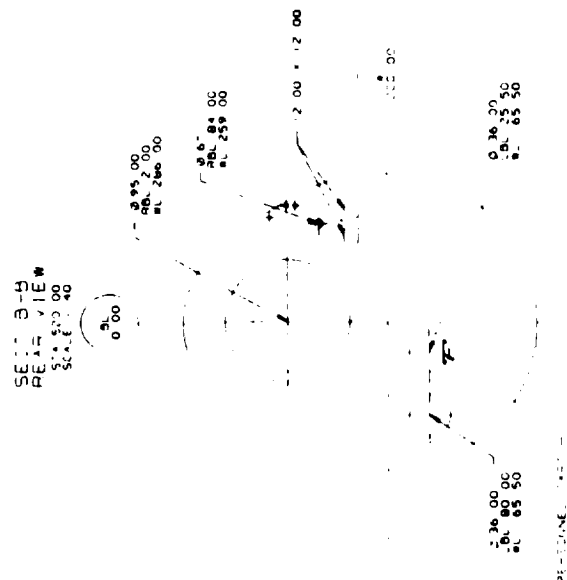
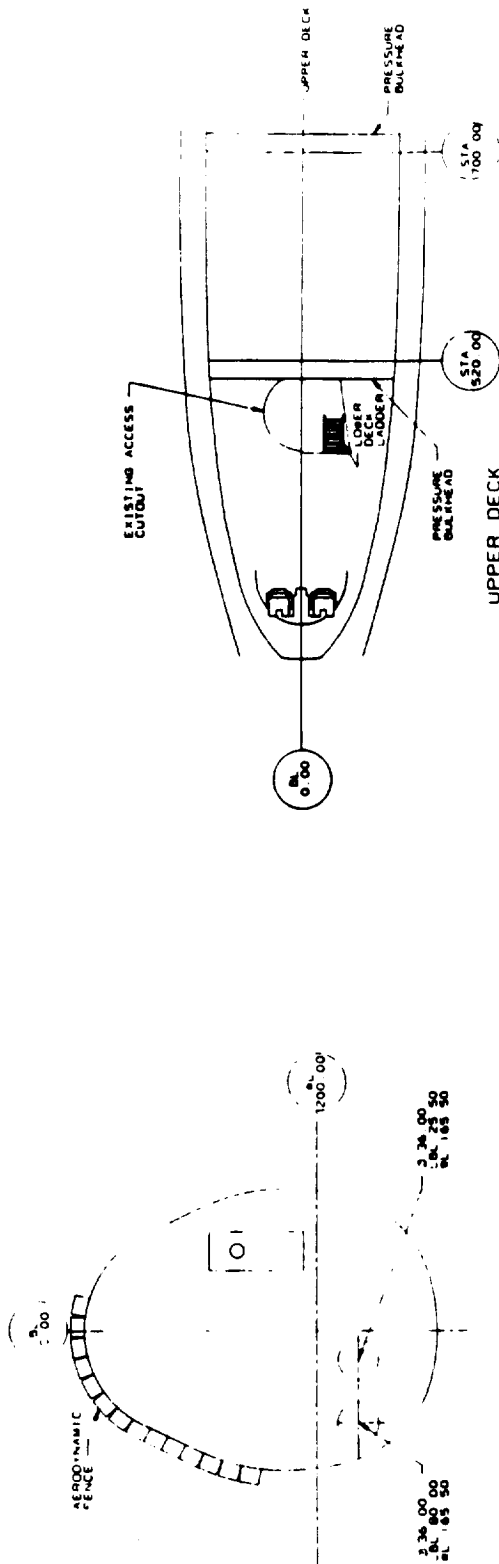


## LAYOUT FOR PERSONNEL ACCOMMODATIONS (LOPA) (CONTD)



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OF POOR QUALITY

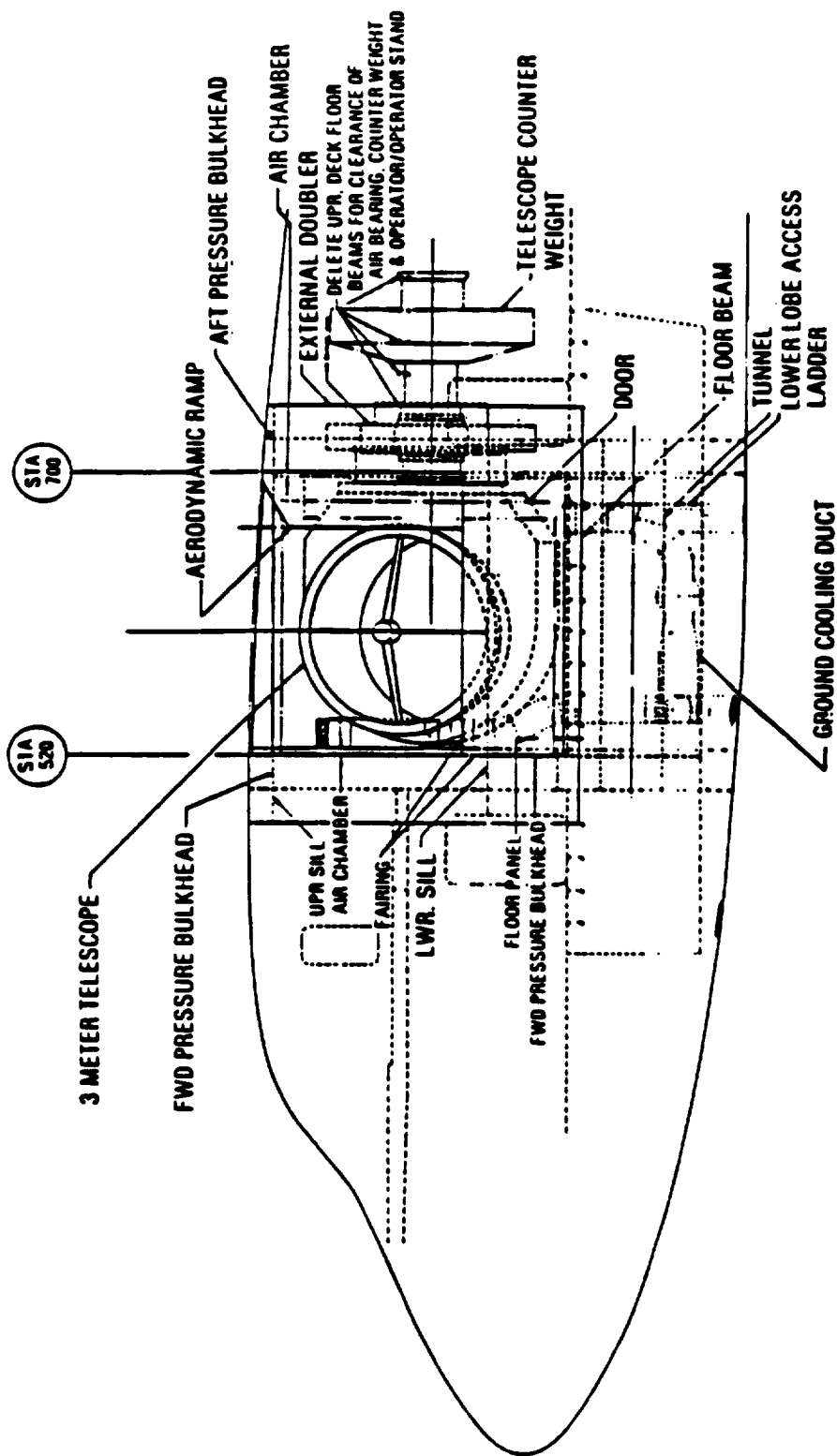
### LAYOUT FOR PERSONNEL ACCOMMODATIONS (LOPA) (CONTD)



### Cavity Modification Concept

The drawing illustrates the various physical modifications to the forward section of the SOFIA aircraft for accommodating the telescope. The two full-depth pressure bulkheads are shown at aircraft stations 520 and 700; the telescope centerline is at station 601.6 (the numbers refer to inches measured from a forward datum). The upper and lower sills are the extremes of the cavity opening; the two-section door moves within this envelope. The forward end of the cavity is bounded by the forward bulkhead; the aft end is "stopped" by the aerodynamic ramp, which provides for smooth reattachment of the shear layer. Not shown is the boundary layer control (BLC) fence, to be located outside the fuselage ahead of the forward bulkhead. The "air chambers" depicted are plenums to help route air flow around the cavity and assist in thermal isolation; it is currently felt that these add unnecessary complexity and will not be needed. The external doubler is additional structure required to stiffen the remaining fuselage around the cavity. Although the chart shows that the upper deck floor/beams are to be deleted in the area of the counterweight, the actual need for this will depend on the final counterweight configuration selected. (As discussed in Section 3, the counterweight would be more weight efficient if it were longer and narrower). The concept keeps the main deck floor in its standard location in the cavity to minimize modification cost and complexity. The "hidden" ground cooling duct enables transfer of cold air from the ground cooling system, through a fuselage port, to a port in the cavity floor.

### SOFIA CAVITY CONCEPT (LEFT-HAND SIDE VIEW)

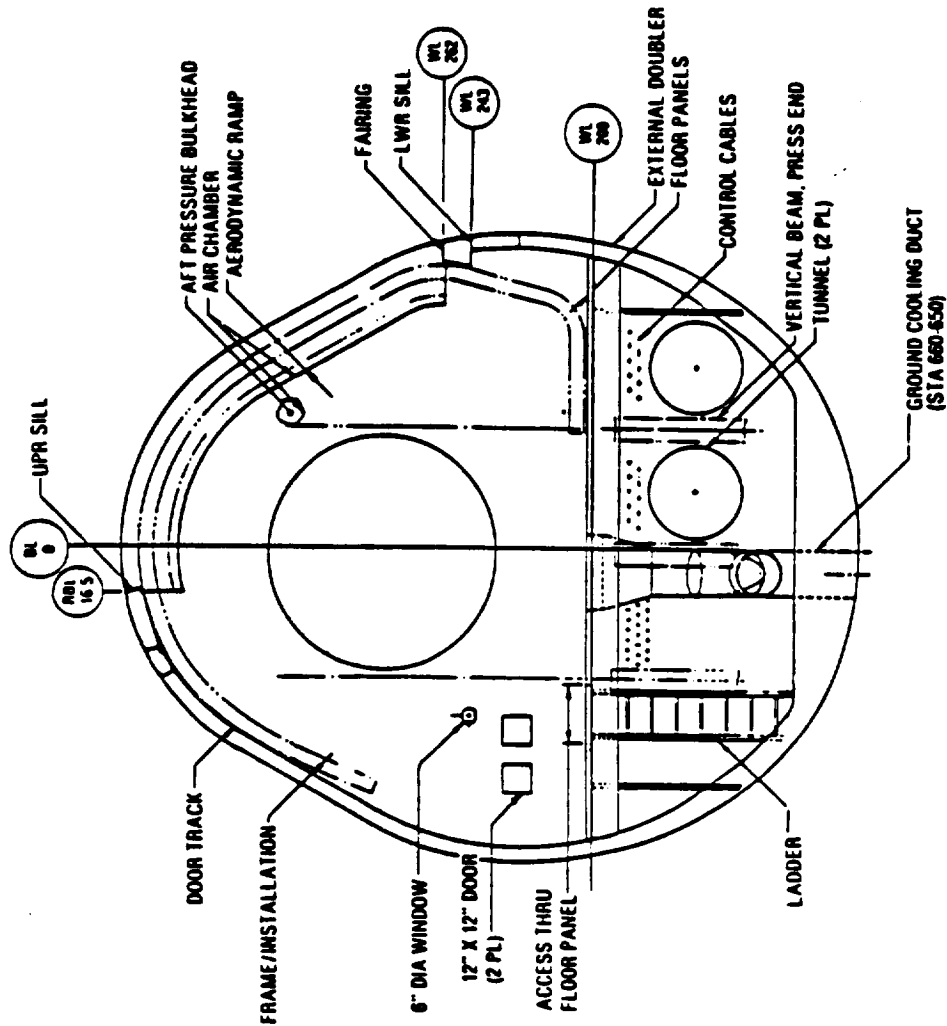


## **Cavity Modification Concept (Contd)**

### **Aft Cavity Bulkhead Layout**

The figure depicts the layout for the F.S. 700 pressure bulkhead, with associated provisions (note that this view is looking aft - telescope points to the right). The main features shown are: the upper and lower sills for the cavity opening; the upper and lower cavity door tracks; the aerodynamic ramp location; two 12-inch square doors for small equipment and a 6-inch diameter window; the floor panel and external doubler locations; the vertical sub-floor structural beams; aircraft control cable rerouting locations; the two sub-floor transfer tunnels; the ground cooling duct routing; and the access hatch and ladder leading from the main cabin floor to the lower floor for tunnel access.

### AFT PRESSURE BULKHEAD LAYOUT



## Cavity Modification Concept (Contd)

### Aft Cavity Bulkhead Structure

The aft bulkhead of the cavity housing the telescope is designed for 18.8 psi pressure (the ultimate pressure load based on 2 factors of the maximum relief pressure of 9.4 psi, for normal operating pressure of 9.0 psi). The construction consists of horizontal beams at 20 inch spacing with a moment of inertia ranging from 600 to 1500 in<sup>4</sup> ("areal moment") depending on beam length and location. The beams are 20 inches deep and are "strength designed". This design maintains maximum deflection limits of 1/2 degree rotation of the bulkhead at the telescope rotation axis, at 9.4 psi. 20 inch long vertical stiffeners are located every 10 inches.

The main beams (2 vertical and 2 horizontal) surrounding the air bearing cutout as well as other highly loaded beams are made failsafe by using dual chord caps and web. Additional beam strength at the center of the bulkhead is provided by adding radius extrusions that can be tailored for loads to save weight if required. The bulkhead web is .080-inch 2024-T3 aluminum for pressure, with .040-inch bonded straps at beam locations to prevent tearing at fasteners. Beam chords in tension are 2024 material and chords in compression are 7075 material. Loads from the bulkhead are transmitted to the side of the body skin with intercostals located between existing stringers. The telescope support consists of a closed torque box attaching to the telescope at the inner circle and to the bulkhead at the outer perimeter with internal ribs every 15 degrees from the inner circle radius. The torque box depth is 10 inches, with .063 gage 2024 skins. The chord members of the inner circle are sized to maintain a constant (as close as possible) deflection under pressurization at points of contact with the air bearing.

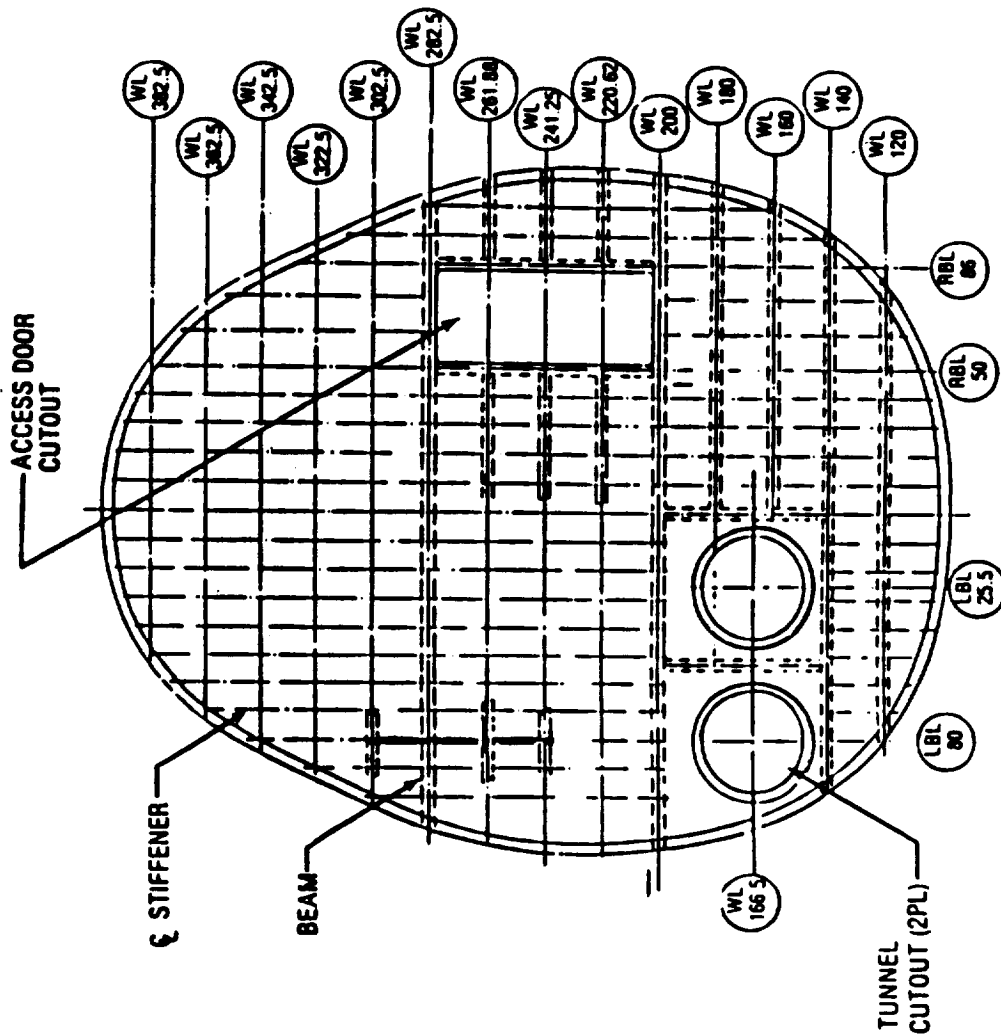
This is a highly detailed technical drawing of a mechanical component, possibly a turbine or engine part, shown in a cross-sectional view. The drawing is oriented vertically on the page. It features a large central circular opening. The interior of the component is filled with a complex network of lines representing internal structures, including what appears to be a series of vertical blades or vanes on the right side. There are several smaller circular features, some of which are labeled with numbers (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100). The drawing is heavily annotated with lines, circles, and text, indicating a detailed engineering plan. The overall shape is roughly circular, with a complex internal structure that suggests a high-precision mechanical part.

## Cavity Modification Concept (Contd)

### Forward Cavity Bulkhead Structure

The F.S. 520 (forward) pressure bulkhead is also designed for 18.8 psi (2 factors on relief value). The construction is similar to the aft bulkhead, except it contains no air bearing cutout, but has a forward opening plug door measuring 40x80 inches for access to the cavity. This bulkhead contains a slip joint for the telescope locking "truunion" to compensate for relative deflection occurring between the two bulkheads, from pressure loading variation. The bulkhead is strength designed with areal moments ranging from 600 to 1000 in<sup>4</sup>, depending on beam location and length. The loads from the bulkhead are transmitted to the side of body skin with intercostals between the stringers, extending forward of the bulkhead. The bulkhead to skin intercostals are basically back-to-back angles for failsafe design, located between existing body stringers. The higher-loaded intercostals will spread the load over 40 inches (2 frame bays) in length; others will be 20 inches long. The "kick" loads or radial frame reactions will require further analysis to verify design adequacy.

### FORWARD BULKHEAD STRUCTURE

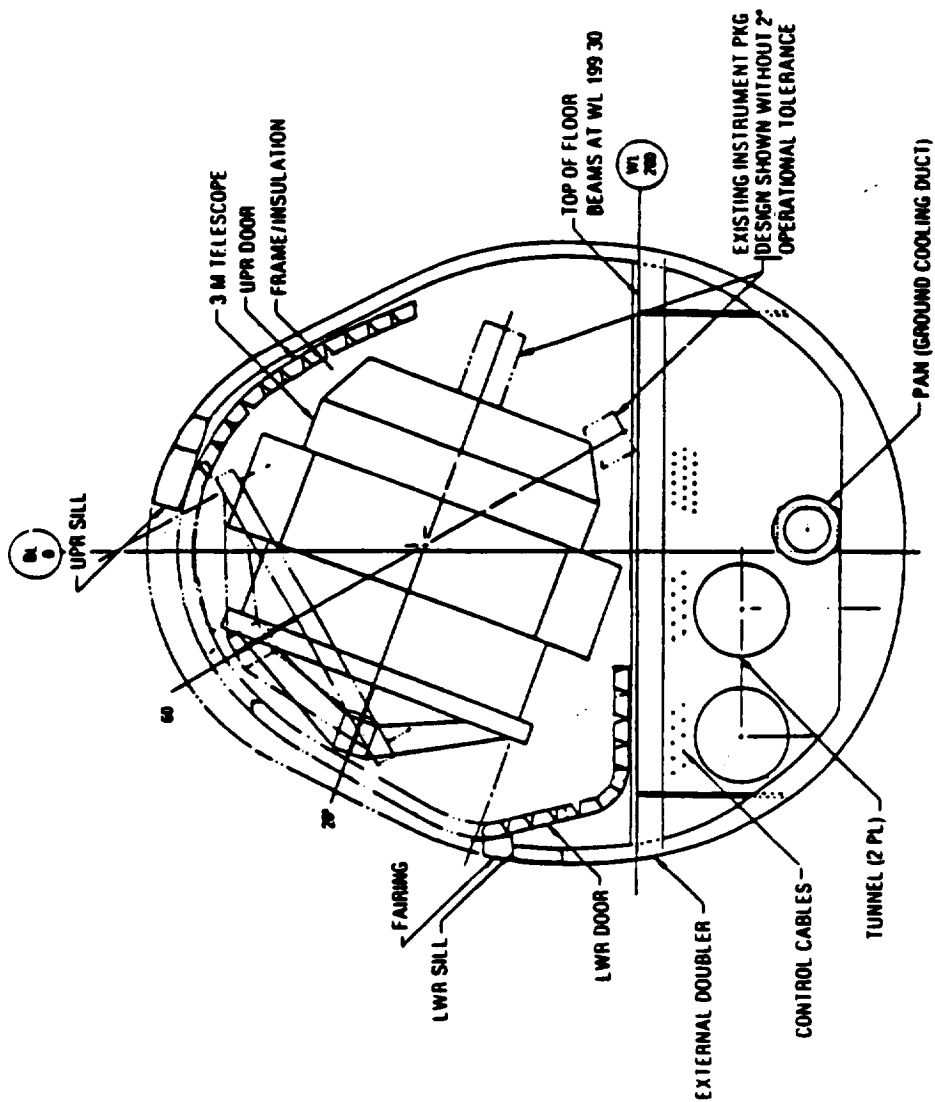


## Cavity Modification Concept (Contd)

### Cavity Geometry

The drawing depicts the cavity volume available at the telescope centerline, located at F.S. 601.6. The 3-meter telescope conceptual design, provided to BMAC by ARC, is shown in its two extreme elevation positions, 20 and 60 degrees above horizontal. As can be seen, clearances are not generous. In fact, the rear-mounted Cassegrain instrument shown impinges on the cavity floor at the higher elevation; however, it is improbable that instruments of this length will be necessary. A more serious issue is the proximity of the heading to the upper cavity door, and of the primary "tub" to the floor, at the high elevations. It should be noted that this drawing only depicts a "centered" telescope, so that if the current  $\pm 2^\circ$  cross-elevation angular range is factored into the "dynamic envelope", clearance becomes almost nonexistent. (Indeed, there may be a need to increase the cross-elevation range due to science considerations). In addition, the vibration isolation system travel, which may be up to  $\pm 1$  inch in turbulent conditions, adds directly to the telescope envelope. The location of the center of rotation (air bearing centerline) has been established with all the clearances in mind, so little can be gained by moving it. These factors point up the need for continuing coordination and design optimization for both the telescope and cavity. The location of "stress points" having been established, it is incumbent on both sides to improve clearances in these areas by modifying geometry, if possible. To a large extent, this has already been accomplished in the cavity design, in that the upper door track has been located as close to the fuselage as possible. Of course, the ultimate resolution, if it becomes necessary, is a reduction in telescope size or motion ranges. It has already been established that "bulging" of the fuselage skin or lowering the floor would be quite cost prohibitive (this issue was studied in an earlier concept for a 3.5 meter telescope).

### CAVITY GEOMETRY



## **Cavity Modification Concept (Contd)**

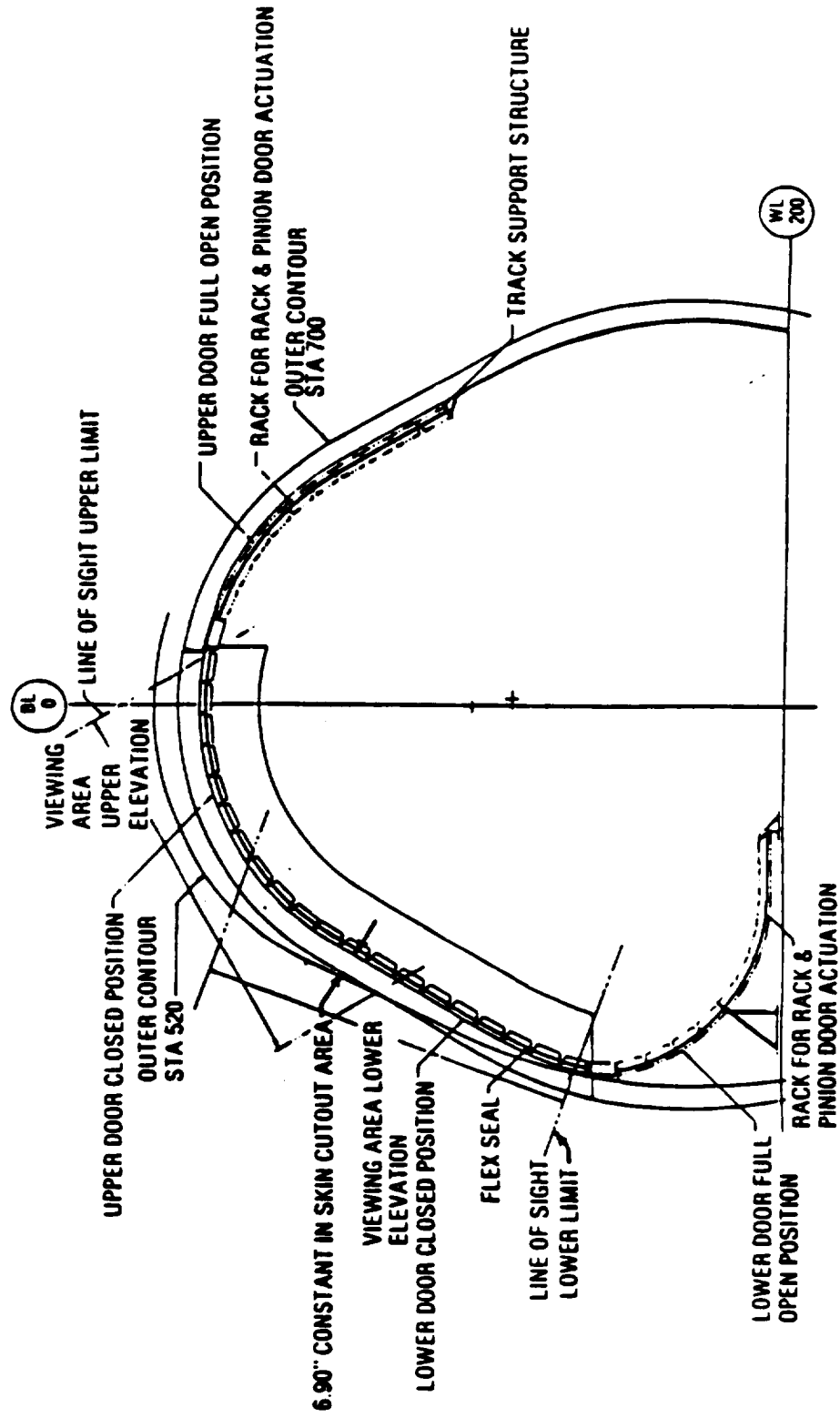
### **Cavity Door**

The figure illustrates the concept developed for the cavity open port door installation. The concept has evolved to a configuration which permits penetration of the aft aerodynamic ramp by the door structure. To accomplish this, the concept utilizes a flexible aerodynamic seal over the ramp, which is positioned and controlled by rollers on the door segments operating like a roll-top desk. The flexible seal smooths the airflow over the ramp and is normally open when the door is closed, and is in a sealing position when the door is open. Environmental seals are provided at other door locations to preclude water penetration into the cavity.

With this configuration, the forward and aft door tracks can be located in line. Two track rollers are located at each segment joint which (with shared rollers) provides four track rollers per segment at each end. Fore/aft stability is provided by grooves in the aft track; the forward track is smooth and allows for structural deflections up to 1/2 inch. Each door segment is designed as a box structure with machined end fittings and hinges at top and bottom. The complete door is comprised of two sections of eleven 10-inch segments each; the upper section rolls up and the lower rolls down allowing the doors to track telescope elevation changes. The doors are actuated by a rack and pinion drive system located on the bottom segment of the lower door and the top segment of the upper door. Thus the racks are contained within the fuselage, permitting rigid structure between forward and aft racks to avoid binding. Suspension points from primary structure are chosen for minimum induced deflections.

The door extends from F.S. 523 to F.S. 683; its depth is 4 inches with an .040 outer skin and .040 inner skin, with access holes for pressure relief and fastener installation access. Bonded skin bands at the edges of the outer skin and rib locations will provide extra thickness for countersunk fasteners. Ribs are added every 20 inches along the door length for panel breakers and to hold door shape. Pressure difference over the entire door is 1.5 psi maximum, ultimate.

## CAVITY DOOR INSTALLATION



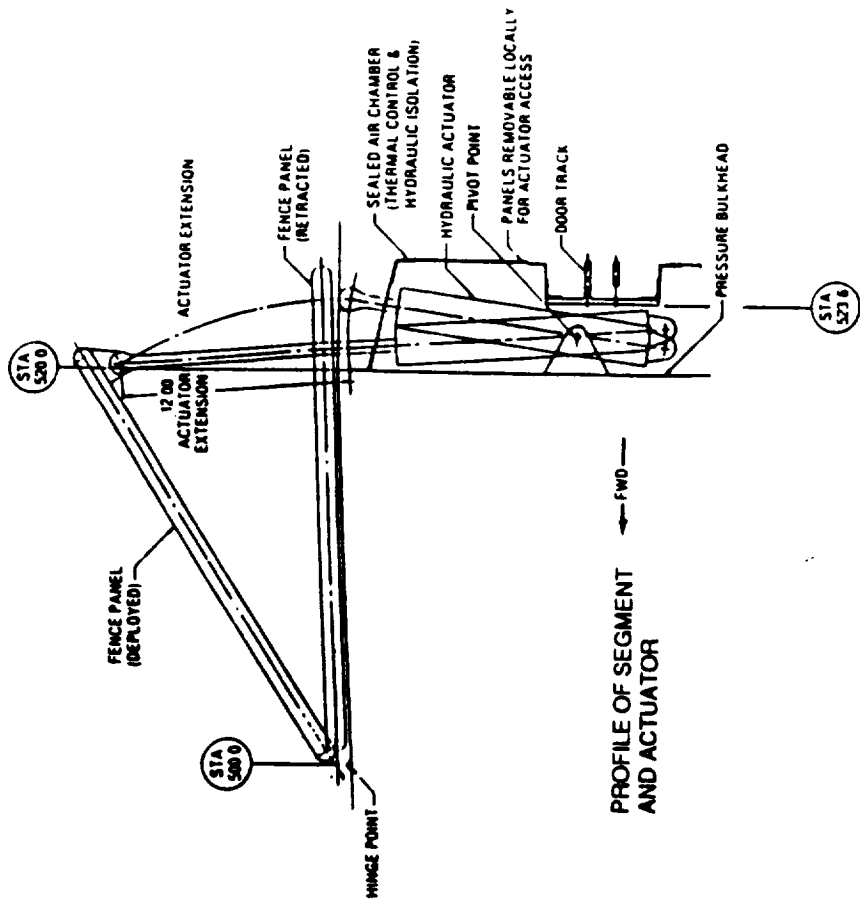
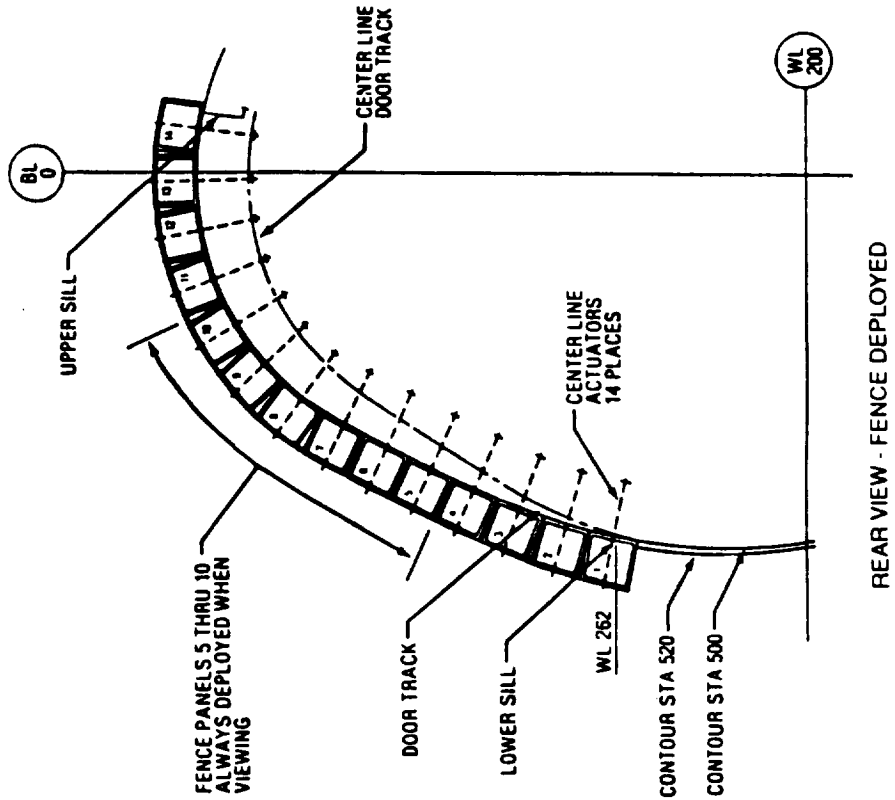
## Cavity Modification Concept (Contd)

### Shear Layer Control

There are many options for controlling the shear layer over the cavity open port; a well-behaved, continuous shear layer is important for minimizing the effects of "seeing" on telescope optical performance. Main options include a passive aft ramp alone, an aft ramp with active blowing from the forward bulkhead, and a forward external fence with aft ramp. The latter configuration has been chosen as a conservative approach with minimum complexity for this study phase; future computational analyses and wind tunnel testing will be needed to determine the optimum configuration.

The figure shows a rear view of the deployed segmented fence, which is mounted on the fuselage forward of the cavity. The fence consists of a series of individually actuated porous panels. Each panel is approximately 25 inches and is constructed with a frame of stainless steel tubing, welded at each corner and covered with a screen. The screen is a thin gage stainless steel sheet completely perforated with 3/16-inch diameter holes of 1/4-inch centers; it is welded all around to the tube frame. A hydraulic "piston" actuation system was chosen to deploy the panels approximately 30° from contour; the individual actuation concept allows the fence to "track" the telescope in elevation angle and, in turn, the open port area of the door. Having the fence only partially deployed (approximately 8 of 14 panels) at any given time improves aircraft performance by reducing drag. The aerodynamic aft ramp is sized for air impingement at 7.5° off contour from the forward lip, and is installed on the aft bulkhead with a flexible seal cutout for the door penetration.

### AERODYNAMIC FENCE CONCEPT



## Aircraft Modification Stress Analysis

The BMAC aircraft system concept study included performance of stress analyses in various areas, including fuselage reinforcement around the open port, pressure loads and telescope cutout in the aft bulkhead, pressure loads and access door in the forward bulkhead, and the floor tie in the bulkhead design. For the aft bulkhead the overall arrangement was studied extensively, and the proposed concept utilizes uniquely sized beams in a lattice arrangement, with overall and relative displacements manageable at efficient material working stresses. The air bearing to bulkhead interface arrangement with radial intercostals from bearing to sills and torque cells resulted in bearing to bulkhead relative deflections and loads that are manageable. The critical design load on the aft bulkhead (by a large margin) is pressurization, and all critical bulkhead elements are split for fail-safe damage tolerance.

The forward pressure bulkhead has the same general arrangement except for the access door framing and reinforcement required. The non-pressurized cavity floor currently baselined requires shear-only connection to bulkheads, with the induced loads and deflections from the bulkheads disabled. Unstiffened honeycomb panels are proposed as the best option, with the lower face sheet used to replace part of the torsional stiffness lost in the cavity cutout area; the upper facesheet helps carry bending loads, local personnel walking and other "abuse" loads. For and aft slots are provided at both ends of panel to release axial load capacity of panel caused by large relative deflection of the two bulkheads. (An alternate pressurized floor concept was also studied and is considered viable, with some weight penalty.)

For the cutout and monocoque sizing, the overall size of the open port is the primary driver. Various cutouts, sizes and bulkhead stations were studied. The ramp and fence loads and stiffening requirements have not been definitized to date; however, the approximate geometry appears feasible. Further study is also required for the monocoque reinforcement, with the final configuration dependent on stiffness as well as static load requirements. The preliminary door concept is complete and appears feasible; however, dynamic environments are still to be investigated to verify the initial design.

**STRESS ANALYSES**

- FUSELAGE REINFORCEMENT
  - CUTOUT AND MONOCOQUE SIZING
  - RAMP AND FENCE
  - MONOCOQUE REINFORCEMENT
  - CAVITY DOOR
- AFT BULKHEAD
  - CUTOUT FOR TELESCOPE AIR BEARING
  - PRESSURE LOADS
- FORWARD BULKHEAD
  - ACCESS DOOR
  - PRESSURE LOADS
- CAVITY FLOOR
  - BULKHEAD CONNECTION
  - AIRCRAFT TORSION AND BENDING
  - PERSONNEL AND "ABUSE" LOADS
  - ALTERNATE PRESSURIZED CONCEPT

### Modified Aircraft Drag Analysis

Drag increments were estimated for the current configuration with an open port 180" x 210" in size, an aft ramp and a KAO-like fence forward of the open port. Four basic modes and fence/door positions were studied. They are: 1) Flight mode, where the door is closed and fence retracted, for takeoff, climb, descent and landing and ferry flights; 2) Observation "Mode I" with fence retracted and doors partially open and tracking the telescope, for comparison with fence deployed mode; 3) Observation "Mode II" with door and fence tracking the telescope (current baseline); and 4) Observation "Mode III", with door fully open and fence fully deployed, representing a back-up or emergency mode of operation, giving worst-case drag and probable strong buffeting.

The drag analysis was conducted by estimating the effects of each of the drag producing elements, shown as a "flat-plate equivalent" in square feet, and summing the increments for total drag in each mode. The elements are: a) forward lip and aft-facing step, which is the surface "step-down" from the forward fuselage skin to the door contour; b) the aft ramp with corrections for the gaps; at the aft edge of the door and the contribution of the gap covers over the door hanger/track follower; c) the door surface (closed, open, or tracking) with corrections for the upper and lower sill and the grooves/gaps between the door segments and circumferential gaps; d) constant correction for the removed skin in the open port area (this is subtracted); e) fence retracted (ID), fully deployed (U), or tracking (T), including fence porosity; and f) "interference" effects corrections, such as drag generated by flow changes on or around adjacent surfaces and the wing root/body intersection; a nominal 10% of the other drag increments was assigned for this parameter in each mode.

### SOFIA INCREMENTAL DRAG SUMMARY

	Forward Lip	Alt Ramp	Door Closed (C) Open (O) Tracking(T)	Less Removed Skin	Fence Down (D) Up (U) Tracking (T)	Interference 10%	Summary
Flight Mode: (Least Drag, for Climb & Ferry)	3.72 sq ft	.40 sq ft	(C) 2.46 sq ft	.92 sq ft	(D) 1.65 sq ft	.73 sq ft	8.0 sq ft
Observation Mode I: Fence Retracted, Door Tracking	5.90 sq ft	.55sq ft	(O&T) 1.12 sq ft	.92 sq ft	(D) 1.65 sq ft	.84sq ft	9.1 sq ft
Observation Mode II: Door & Fence Tracking	5.90sq ft	.55 sq ft	(O&T) 1.12 sq ft	.92 sq ft	(U&T) 12.30 sq ft	1.90 sq ft	20.9 sq ft
Observation Mode III: Door Full Open Fence Full Deployed	8.9 sq ft	.64 sq ft	(O) .06 sq ft	.92 sq ft	(U) 18.09 sq ft	2.68 sq ft	29.4 sq ft

### Aircraft Mass Summary

The chart shows a breakdown of the SOFIA aircraft mission weight and center of gravity; the latter is given in terms of the "balance arm" in inches from a forward datum, and percent of "mean aerodynamic chord" which is used to evaluate c.g. limits relative to the allowable envelope. The SOFIA "pre-mod" operating empty weight (OEW) is the basic 747SP dry weight with approximately 60,000 lbs of standard airline provisions deleted; the main deleted items include galley structures and food, life rafts and beacons, escape slides, passenger accommodations, cargo handling equipment, some doors and windows, etc. Addition of the "baseline" payload and ballast (see breakdown in Section 3) gives the "Projected SOFIA Zero-Fuel Weight" of about 338,000 lbs. The fuel load shown is for a maximum endurance mission (e.g., for ferry or deployment). For a typical science mission, the maximum ramp or taxi gross weight envisioned is ~ 485,000 lbs, to allow direct ascent to 41,000 ft., and maintain that altitude with door open and fence deployed. This means that the science mission fuel load is about 147,000 lbs. Aircraft endurance at operating altitude is shown on the next chart, against payload and drag.

### **SOFIA WEIGHT AND C.G. SUMMARY**

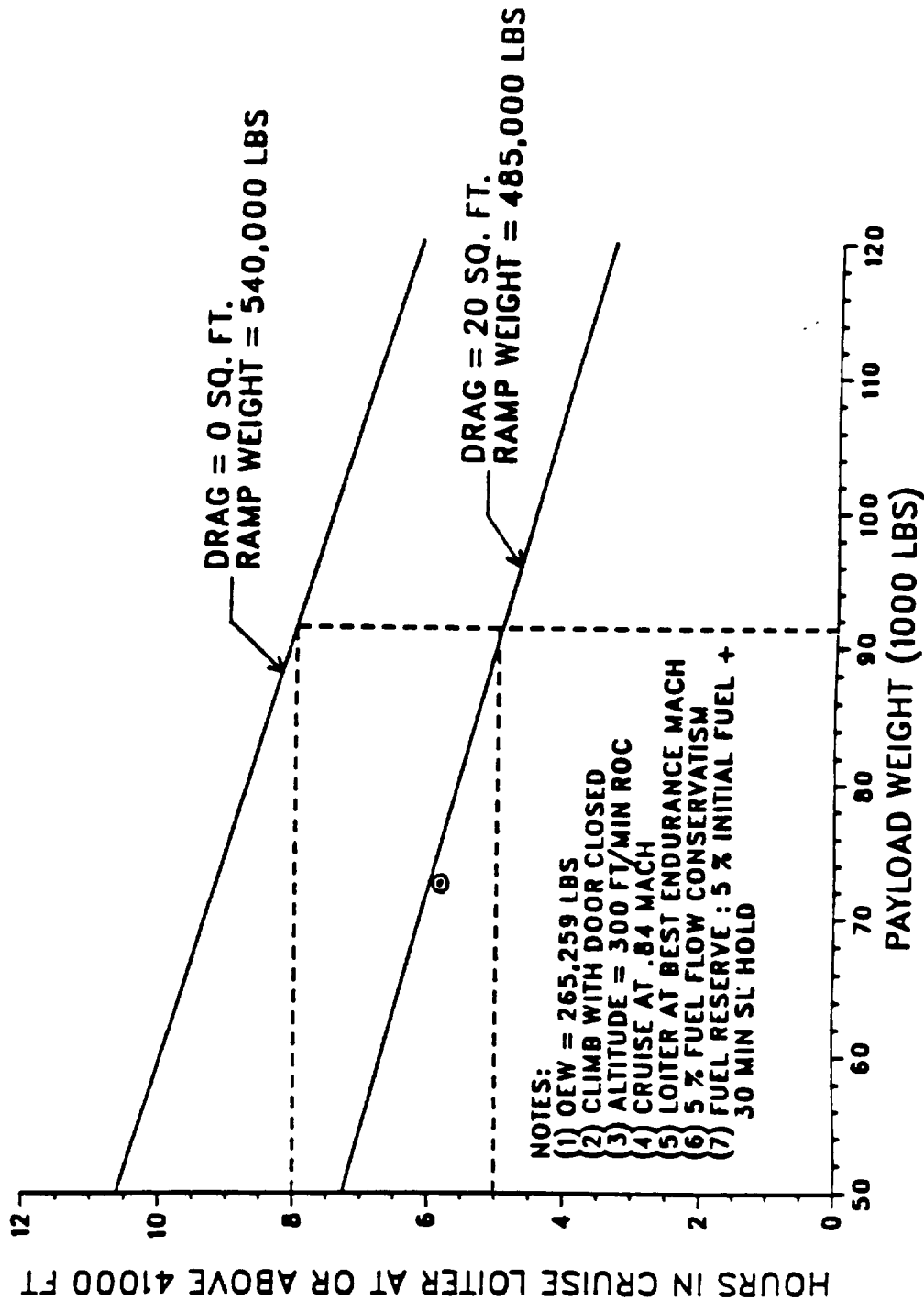
	<u>WT</u>	<u>BA</u>	<u>% MAC</u>
SOFIA PRE-MOD OEWS	266,035	1338.8	
PAYLOAD	61,785	1042.0	
BALLAST	10,020	2060.0	
PROJECTED SOFIA ZFW	337,840	1305.9	14.6
FUEL	347,985	1279.3	
TAXI GROSS WEIGHT	685,825	1292.4	10.5

### Aircraft Performance for Science Mission

The chart shows the "standard" Boeing 747SP (i.e., with existing engines) performance capability for the SOFIA science mission. The critical parameter, time at or above 41,000 ft., is plotted against payload weight for two cases of drag increment. Entering assumptions are operating empty weight (after airline equipment deletions), climb with door closed/fence retracted, operation at cruise ceiling (allowing 300 feet/minute climb capability - standard), cruise at most efficient speed (Mach 0.84), loiter at best endurance Mach, 5% conservatism on expected fuel flow, and a standard fuel reserve for instrument flight rules (IFR) operation.

The chart was developed during an earlier study phase, when total payload was expected to be above 90,000 lbs. The current payload plus ballast goal of ~ 72,000 lbs with 20.9 square foot drag increment allows approximately 5.8 hours at or above 41,000 feet, for a 485,000 lb. ramp weight. Achieving the firm requirement of 6.5 hours at altitude therefore requires improvement in mass, drag, and/or engine performance. As previously shown, mass margins for the 3-meter telescope (with given image quality requirements) are non-existent to meet its goal. Other mass estimates are also felt to have no margin. The performance sensitivity to drag points up the need for wind tunnel testing to establish the minimum drag configuration which gives adequate shear layer control; for instance, deletion of the fence would reduce the drag increment to approximately 8 square feet, allowing altitude endurance to increase by about 1.5 hours. An option of last resort is use of "enhanced thrust" engines, which entails operating the available power plants at higher than standard continuous power settings while at altitude, accepting increased maintenance requirements and costs. Of course, more powerful (new) engines are also available, which could be installed for a large cost increase.

## AIRCRAFT PERFORMANCE FOR SCIENCE MISSION



## Aircraft System Design Drivers

BMAC conducted an analysis to identify mission and telescope system requirements which are design drivers for the aircraft system design. Specifically, the effects on aircraft system design for small changes (10 percent) in these design driving requirements were analyzed, with results shown on the requirements sensitivity matrix. The matrix shows the trend of costs and performance for the changes from the baseline as noted: telescope size (envelope) decreased by 10%; payload weight decreased by 10%; aperture size (i.e., open port) decreased by 10%; aero-optics interface (fence deletion); and science mission capability ( $\pm 10$  percent time at altitude). The only change from the Phase A baseline that caused any significant change in design cost was deletion of the porous fence. There would be a small change in the design effort associated with reducing the telescope size, aperture, and weight, but it would be insignificant.

All of the requirements changes that impact the aircraft modification impact the build cost. As the number, size and weight of the modification assembly/parts decrease, the build cost would decrease. There would be no impact on design or build costs for changing the time on station, since this does not affect the aircraft modification. All of the requirement decreases would result in an aircraft performance increase, proportional to the decrease in drag or weight. Increasing on station (at altitude) time by 10% would result in a 600 foot decrease in initial cruise altitude. The "mission" (science) performance would be proportionally decreased when the telescope/aperture size is decreased.

No change in mission performance due to the decrease in payload weight is based on the assumption that the weight reduction does not affect the quality of the optical components. At this time, there is not adequate data available to conclusively predict the impact that the reduction of the porous fence would have on mission (science) performance. Increasing the time on station would not affect mission performance except for the obvious increase in astronomical observation time available; however, the associated increase in water vapor overburden would decrease observational sensitivity.

### REQUIREMENTS SENSITIVITY

Baseline	Change	Design Cost	Build Cost	Aircraft Performance	Mission Performance
Telescope Size 3.0 Meter F-1	-10%	No Change	Decreased (Slight)	Increased (Slight)	Decreased
Payload Weight 62,465 lbs	-10%	No Change	Decreased (Slight)	Increased (Slight)	No Change
Aperture Size FOV 20° - 60° ± 2° 3.0 Meter	-10%	No Change	Decreased (Slight)	Increased (Slight)	Decreased
Aero-Optics Interface Fence and Alt Ramp	Alt Ramp	Decreased	Decreased	Increased	???
Scientific Mission Altitude - 41000 ft. Time on Station 7 hours	± 10% Time On Station	No Change	No Change	± 600 Ft. Change in Initial Altitude	No Change

## 5.4

### Cavity Environmental Control

#### Objectives

There are two objectives for the cavity's environment control. The first is the ability to cool the cavity and Telescope to  $-30^{\circ}\text{F}$  with a one hour time constant. The second requires that condensation never occur within the cavity.

#### Constraints

The airborne environmental control equipment also has a set of constraints that must be adhered to. These constraints include temperature and pressure. Parts must operate at low temperatures ( $-40^{\circ}\text{F}$ ) and pressures (2.7 psia).

Weight must also be restricted, as it is a critical factor for SOFIA. Since the telescope already adds a considerable amount of weight forward, it is critical to minimize support equipment weight there. A circulating fan and reheat coil will add approximately 400 lbs, while having those along with the cooling coil adds about 2000 lbs. The ground based cooling equipment that is off loaded at each base of operations is expected to weigh approximately 15,000 lbs.

Naturally any system that is chosen will require modifications to meet SOFIA's unique needs. For one, it must be arranged to fit inside the existing cargo bay. Our equipment would require (2) 64"x96"x125" pallets. Second, the motors must operate off aircraft 400 Hz power. Another might be to add hydraulic mobility to the pallets.

### **CAVITY ENVIRONMENT CONTROL OBJECTIVES AND CONSTRAINTS**

#### **OBJECTIVES:**

- COOL CAVITY AND TELESCOPE TO -30°F, WITH A ONE HOUR TIME CONSTANT
- CONDENSATION SHALL NEVER OCCUR WITHIN THE CAVITY

#### **CONSTRAINTS:**

- DIMENSIONAL SIZE
- 400 Hz POWER
- LOW TEMPERATURE OPERATION
- LOW PRESSURE OPERATION
- MOBILITY
- FLEXIBILITY
- SELF-CONTAINED
- WEIGHT

## Cooling Approach Options

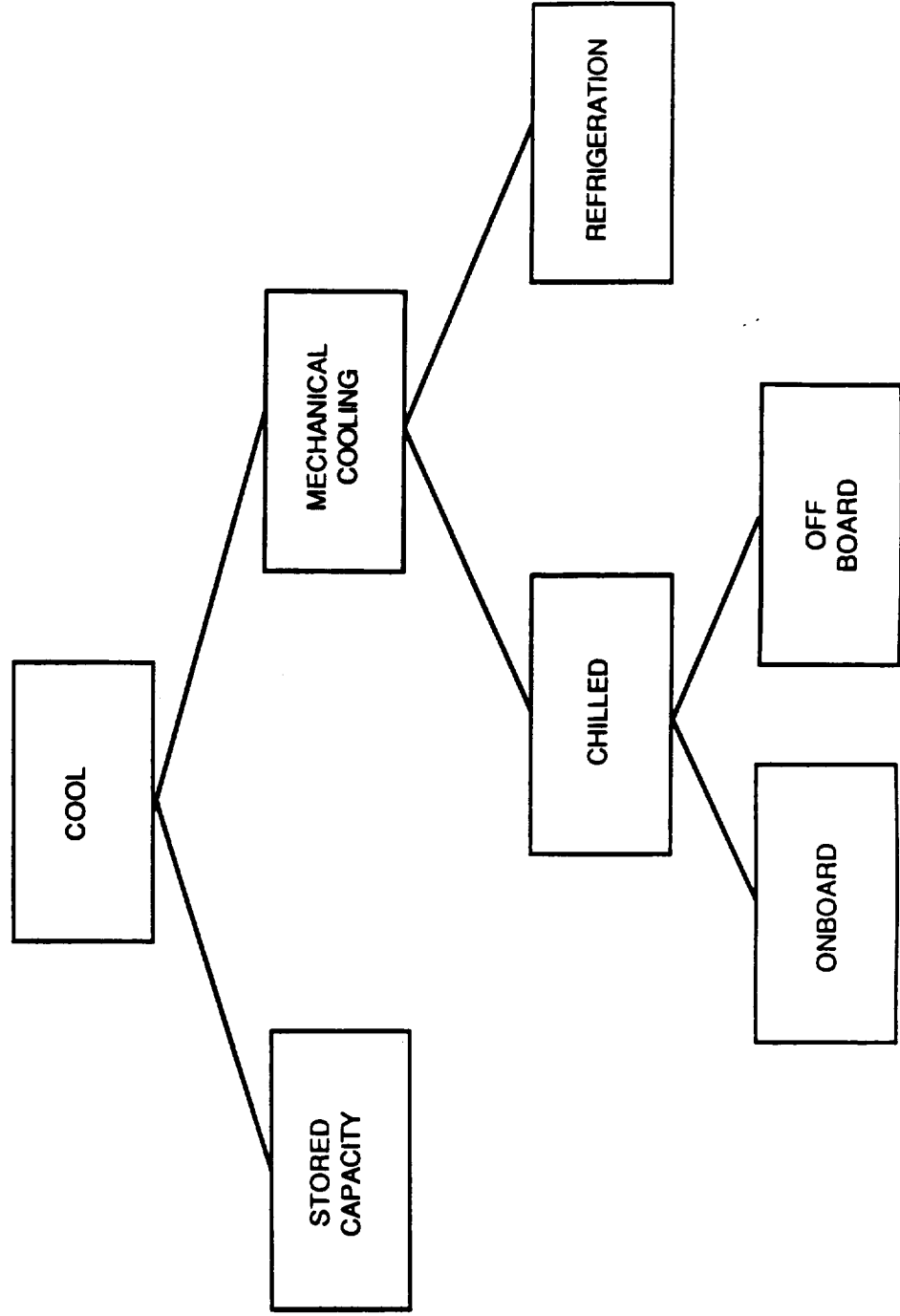
Cavity cooling will best be accomplished using mechanical refrigeration. A typical unit could consist of a modified stock cascade refrigerant system (e.g., Edwards CL15-013-AHP). This system supplies -40°F brine with a capacity of 131,000 BTU/HR at an 85°F condensing temperature. With this equipment a time constant of approximately one hour can be achieved. An air cooled condenser yields mobility and flexibility to the system.

Direct expansion, that is, using the refrigerant to cool air directly, rather than cooling an intermediate fluid, could be used. Unfortunately, it is more difficult to control the refrigerant than the fluid. Therefore, the chilled brine alternative was chosen.

Stored capacity could be used for cooling. A good source would be to use liquid nitrogen; it's common and relatively easy to obtain. It does have drawbacks, however. One is quantity; each flight would require 450 gallons. This capacity has to either be carried on the aircraft or delivered to it at the airstrip. The first alternative causes large shifts in the aircraft's center of gravity. It also lowers the maximum operating ceiling - extra weight translates into lower observation altitudes. The second alternate yields an extra logistics headache (if the liquid nitrogen is indeed available).

The cooling medium for the cavity is air. The air can be cooled on- or off-board the aircraft. There are advantages and disadvantages to each method. Disadvantages associated with off-board cooling include large aircraft penetrations, two fans, and additional pallet area. On-board disadvantages include weight and size penalties in the forward cabin. A roughly 2'x4'x7' airhandler has to fit up front. The cabinet and ducting for the on-board system must form an external pressure vessel. Note that shortcomings for one are strengths for the other method. Off-board cooling was chosen.

## COOLING APPROACH OPTIONS



### Moisture Control Options

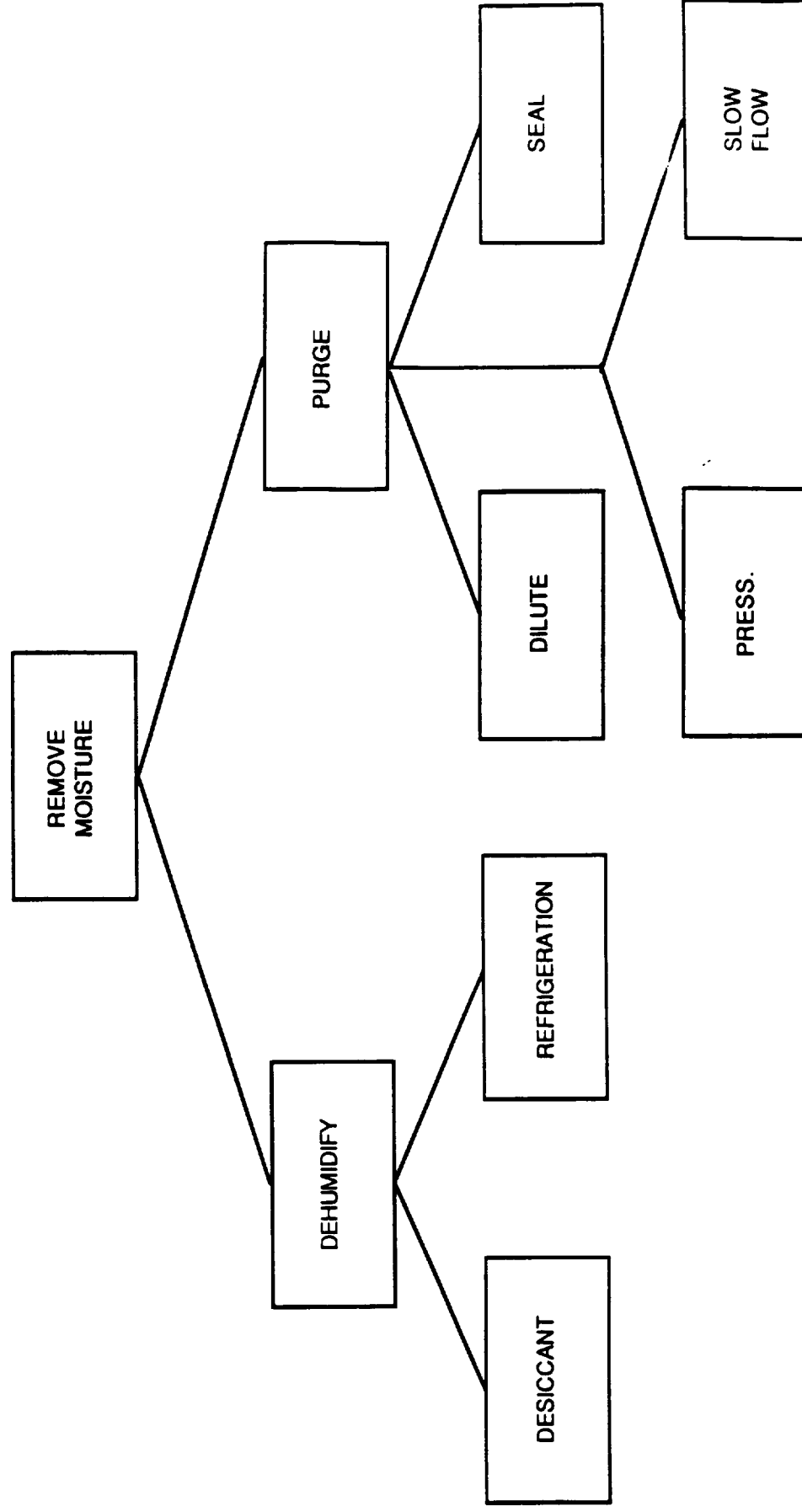
The Telescope equipment requires that condensation never occur. Condensation, whether in liquid or ice form, has a detrimental effect on the mirror and other components. There are four methods for disposing of condensable moisture; two use dehumidification and two use purging.

The purging method uses a supply of dry gas to displace the moisture in the air. The first of the two purging methods examined is the dilution method. This alternative fully mixes dry gas with moist air. Part of the mixture is continuously bled off until a  $-40^{\circ}\text{F}$  dewpoint is achieved. This method uses an unreasonable amount of time and dry gas (62,000 lbm). The second purging method is the laminar flow method. A layer of dry gas is introduced slowly into the chamber. The layer thickens, pushing the moist air out ahead of it. Ideally no mixing will occur between the moist air and dry gas. Although this method would be difficult to control, it only consumes 40 minutes and 90 gallons of liquid nitrogen.

Dehumidification can be accomplished by chemical or mechanical means. Either a regenerative or deliquescent desiccant could provide the necessary moisture removal, but both types require maintenance and post filtration. Regenerative type drying typically requires temperatures in excess of  $200^{\circ}\text{F}$  to reactivate the desiccant. Weight, size and cooling water are also problems. The equipment (from one source) would weigh 7,000 lbs, require 24 gpm of cooling water and be  $7.5' \times 7' \times 13'$  in size. Deliquescent desiccants constantly require disposal and replacement. Both types should be kept out of contact with moisture when not in use. Mechanical dehumidification can be done with the existing cooling coil. A mixing pump and 3-way valve would be added to modulate the coil temperature. In addition to those items an immersion heater is required to defrost the coil. See sequence of operation for further details.

It is desirable to maintain a slightly positive pressure inside the closed cavity. Pressurization excludes warm, moist air from infiltrating the cavity. There are two ways to achieve this goal. The first is to tightly seal the cavity. This would be difficult, so it is not a viable option. Leakage must be allowed for; therefore a supply of dry gas is required to make-up for the gas that leaks out of the cavity. There are two possible sources of dry gas: one is from the compressed air; the other is boiling off stored liquid nitrogen. The estimated leak rate is  $.01 \text{ ft}^3/\text{min}$  at the operating altitude, and  $.05 \text{ ft}^3/\text{min}$  at sea level.

## MOISTURE CONTROL APPROACH OPTIONS

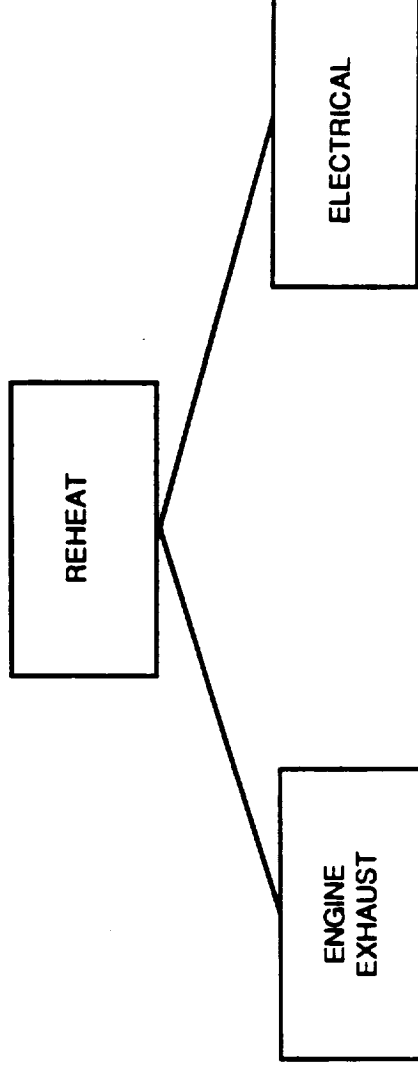


### Reheat Options

The cavity and its contents require heating upon descent. The equipment must be heated up to at least the ground ambient temperature. Thus, when the cavity is opened up on the ground, infiltrating moisture will not condense onto the equipment. An on-board fan (able to supply 4,000 cfm at 1" of water) and heater ((2) 15 kw) could provide this capacity. A heating rate of 100,000 BTU/HR is necessary to obtain a 3 hour warm up.

Two possible methods of achieving the heating requirement are: 1) bleed hot, compressed air from the engines, or 2) electrical resistance heating. Resistance heating is the most feasible. It doesn't require any engine modifications, and it provides simpler capacity control.

## **REHEAT APPROACH OPTIONS**



## Sequence of Operations

### Preparation for Ascent

Before each flight the cavity must be cooled. First, the ground-based cooling unit must be connected to an auxiliary power supply. Then the air supply trunk lines have to be secured to the aircraft under belly, and the cooling unit is activated.

The cooling unit, consisting of an air cooled chiller and a fan-coil unit, supplies  $-40^{\circ}\text{F}$  water to a 3-way mixing valve. The valve mixes the necessary amount of supply and return brine to maintain the desired coil temperature. A mixing pump equipped with a pressure regulated bypass and a heater will be required on the return line to the mixing valve.

The process begins with the fan coil unit being used for dehumidification. The coil temperature modulates as described previously. At first the coil temperature will be maintained at  $33^{\circ}\text{F}$ . Moisture precipitates onto the coil and runs off. Once the return air reaches  $35^{\circ}\text{F}$ , the second stage of dehumidification is enabled. The coil's temperature is gradually lowered to  $-40^{\circ}\text{F}$ . Moisture in the air now freezes onto the coil. Ice build-up on the coil gradually blocks the air flow. Without air flow, cooling cannot occur; therefore the pressure drop across the coil is monitored. When it exceeds a predetermined limit the system defrosts itself.

The defrost cycle first shuts off the  $-40^{\circ}\text{F}$  chilled brine supply. Next, an immersion heater in the return leg is energized. The coil temperature rises to  $70^{\circ}\text{F}$  and is maintained for a short time. During this time, ice is given a chance to melt and run off the coil. It may be necessary to assist the run-off process. Upon completion of the defrost cycle the dehumidification cycle takes over again. Dehumidification continues until  $-40^{\circ}\text{F}$  air is supplied. The  $-40^{\circ}\text{F}$  air is supplied until either an embedded sensor reaches the desired temperature or a certain predetermined cooling time elapses.

In order to eliminate moist, warm air from infiltrating, a positive pressure will be maintained in the cavity. This pressurization, referred to as the purge cycle, begins after the cavity temperature drops below  $35^{\circ}\text{F}$ . The purge cycle basically operates whenever the cavity doors are closed. The system will be disabled upon opening the doors. The purge cycle supplies the necessary dry make-up gas to maintain a slight pressurization of the cavity.

### **SOFIA CAVITY COOLING SYSTEM SEQUENCE OF OPERATIONS**

#### **PREPARATION FOR ASCENT**

1. BEGIN POSITIVE PRESSURIZATION OF CAVITY BY TURNING ON LIQUID NITROGEN SYSTEM
2. START REFRIGERATION/DEHUMIDIFICATION
  - a) CONDENSE MOISTURE OUT JUST ABOVE FREEZING. DRAIN OFF MOISTURE.
  - b) CONTINUE REFRIGERATION/DEHUMIDIFICATION DOWN TO -40°F
  - c) DEFROST THE -40°F COIL WHEN THE PRESSURE DROP ACROSS THE COIL BECOMES TOO HIGH
3. AFTER DEHUMIDIFICATION IS COMPLETE, BEGIN COOLING THE CAVITY USING THE SAME REFRIGERATION SYSTEM AS ABOVE. COOL CAVITY TO -30°F.

## **Sequence of Operations (Contd)**

### **Ascent**

The cavity maintains a positive pressure between itself and the outside. The operation is the same as that described in the final paragraph of "preparation for ascent". Pressurization is terminated upon opening the cavity door.

### **Descent**

After door closure, resume positive pressurization of the cavity. Again, the operation is the same as that in the last paragraph of "Preparation of Ascent". Next, start the onboard circulation fan. Once flow is established, turn the heater coils on. The system heats the cavity until ground ambient conditions are re-established after landing. The door remains closed until reheat is completed.

## **SOFIA CAVITY COOLING SYSTEM SEQUENCE OF OPERATIONS**

### ASCENT

1. MAINTAIN PRESSURIZATION OF CAVITY USING LIQUID NITROGEN SYSTEM. DISCONTINUE AT ALTITUDE.

### DESCENT

1. RESUME POSITIVE PRESSURIZATION OF CAVITY USING LIQUID NITROGEN SYSTEM.
2. HEAT THE CAVITY WITH THE ELECTRIC COILS. CONTINUE TO HEAT EQUIPMENT TO AMBIENT GROUND TEMPERATURE.
3. DISCONTINUE PRESSURIZATION AND HEATING WHEN THE CAVITY EQUIPMENT IS AT OR ABOVE AMBIENT TEMPERATURE.

### Power Requirements

The power requirements for the various components are shown. The ground cooling and purging system envisioned will require a maximum of 61 kilowatts for operation. The onboard heater and fan is expected to need approximately 38 kilowatts; this operation occurs after the science observing is completed.

(1-5)

### POWER REQUIREMENTS

#### CHILLER:

DESCRIPTION	QUANTITY	POWER (EA) kW Hp	TOTAL kW
* HIGHSTAGE COMPRESSOR	1	26.1 (35)	26.1
* LOWSTAGE COMPRESSOR	1	11.2 (15)	11.2
* CONDENSER FANS	3	2.2 (3)	6.6
* SYSTEM PUMP	1	5.6 (7-1/2)	5.6
* BYPASS PUMP	1	2.2 (3)	2.2

#### FAN COIL (EXTERNAL):

* MIXING PUMP	1	5.6 (7-1/2)	5.6
IMMERSION HEATER	1	10.0	10.0
* FAN	1	3.7 (5)	3.7

#### FAN AND REHEAT (ON BOARD):

** FAN	1	2.2 (3)	2.2
** ELECTRIC REHEAT	2	18.0	36.0

#### MISCELLANEOUS:

* CONTROL POWER		.5	.5
HYDRAULIC PUMPS	2	5.6 (7-1/2)	11.2
	TOTAL		109.7 kW

\* SIMULTANEOUS OPERATION, MAXIMUM POWER DRAW 61 kW

\*\* ON BOARD REQUIREMENTS DURING FLIGHT, 38.2 kW

## **Feasibility and Concerns**

### **Feasibility**

Environmental control within the cavity is feasible from both a financial and technical standpoint. It can be accomplished using modified, but for the most part "off the shelf" equipment and technology.

### **Concerns**

More detail is required to define the compressor system. Currently a system similar, though larger (~3 times), than that on the KAO is envisioned. The supply requirement is basically that for the air bearing, which is 40 SCFM.

If the cavity's leak rate is maintained at the level predicted herein, then compressed air could be used for the purge cycle's make-up air requirements. This additional compressed air requirement is small compared to that of the bearing. However, the compressors would be required to operate during the entire mission.

The cooling equipment's power draw borders on the high side. Reducing equipment size would be useful from both a power and dimension stand point. If capacity reductions are made, however, cool down time would require extension.

Dehumidification by desiccant should not be ruled out yet. Some of its drawbacks may not be too difficult to overcome.

## **FEASIBILITY AND CONCERNS**

### **FEASIBILITY**

- TECHNICAL FEASIBILITY ESTABLISHED
- USE OF SLIGHTLY MODIFIED/EXISTING EQUIPMENT ENVISIONED

### **CONCERNS**

- COMPRESSOR SYSTEM REQUIRES FURTHER DEFINITION
- COOLING EQUIPMENT POWER NEEDS ARE GREAT
- DESICCANT OPTION SHOULD NOT BE RULED OUT

## Conclusions

Environmental control within the cavity is feasible from both a financial and technical standpoint. It can be accomplished using modified, but for the most part "off the shelf" equipment and technology.

Cooling and moisture control can be achieved by using a modified low temperature chiller. This chiller would supply -40°F brine to a temperature regulated coil. The coil would be controlled for both cooling and dehumidification. All the above items, including a supply fan, would be palletized. This palletized chilling unit would be left on the ground during observation flights. On board the aircraft would be a reheat coil, fan and minor duct work.

## **CONCLUSIONS**

- TECHNICAL AND COST FEASIBILITY ESTABLISHED, USING MODIFIED AND "OFF THE SHELF" EQUIPMENT
- GROUND COOLING/DEHUMIDIFICATION EQUIPMENT PALLETIZED FOR EASE OF GROUND/AIR TRANSPORT
- REHEAT SYSTEM CARRIED ON-BOARD, WITH MINOR WEIGHT AND VOLUME PENALTIES, AND LOW COMPLEXITY

### Aircraft Interfaces Summary

The chart summarizes the major interfaces between the aircraft system and the other SOFIA elements. Detailed interface requirements have been specified in some areas, as delineated in PD-2000 (e.g., power levels, voltages, etc.), while in other areas only the need for interfaces has been identified (e.g., telescope pointing control/autopilot). An important effort of future project phases will be to establish interface responsibilities, boundaries, and detailed technical requirements.

Under structural/mechanical interfaces, the major aircraft/telescope interface is the mounting of the vibration isolation system/air bearing to the aft cavity bulkhead, for which preliminary drawings have been developed. The cavity also must provide for electrical/communication cable and pneumatic line "feedthroughs" from the cabin to the telescope, and routing of these lines (e.g., "wire curtain") from bulkhead to telescope. Provisions for mounting consoles, racks, seating, etc. must be made in the cabin, with associated wire routing provisions. An attachment interface for ground based cavity cooling/purging equipment must be provided on the fuselage underbelly.

Thermal interfaces include the need for cavity interior insulation to isolate the cavity from the cabin areas and fuselage exterior; preliminary design and analysis of cavity wall liners has been accomplished in this area. An option under consideration is to perform initial cavity precool with standard aircraft air conditioning equipment. Finally, the need for heat rejection from cabin mounted electronic equipment needs investigation, with possible provision of aircraft "heat sinks".

Acoustic attenuation provisions between cavity and cabin may be needed beyond that provided by the bulkheads and thermal isolation "covers". A "sound barrier" curtain is to be installed in the aft cabin immediately forward of the main console. An electrical power distribution panel, with capabilities as specified in PD-2000, has been baselined for location near the sound partition.

Finally, communications interfaces are needed for aircraft data to be provided to the central processing unit of the mission management system (e.g., - aircraft position from INS, and wind vector, temperature, altitude, etc. from air data computer); and a to be determined interface providing capability for tracker operator control of aircraft pointing via the autopilot is needed.

### **AIRCRAFT INTERFACES SUMMARY**

- STRUCTURAL/MECHANICAL
  - TELESCOPE/BULKHEAD MOUNT
  - BULKHEAD FEEDTHROUGHS
  - BULKHEAD TO TELESCOPE CABLE/LINE ROUTING AND ATTACHMENT
  - CABIN EQUIPMENT MOUNTING (CONSOLES, RACKS, ETC.)
  - CABIN CABLE/LINE ROUTING
  - GROUND COOLING EQUIPMENT/AIRCRAFT ATTACHMENT
- THERMAL
  - CAVITY INSULATION
  - CAVITY PRECOOL WITH AIRCRAFT AIR CONDITIONING EQUIPMENT (OPTIONAL)
  - CABIN EQUIPMENT COOLING (IF NECESSARY)
- ACOUSTIC
  - CAVITY/CABIN ISOLATION
  - CABIN SOUND BARRIER
- ELECTRICAL POWER
  - POWER DISTRIBUTION
- COMMUNICATIONS
  - "AIR DATA" INS TO CENTRAL PROCESSOR
  - POINTING CONTROL TO AUTOPILOT

## Conclusions and Major Issues

### Conclusions

The Boeing 747SP remains the platform of choice for the SOPFA mission. Of the several conclusions reached during the BMAC Phase A study, the following four appear to be most significant.

1. The study has confirmed the feasibility of installing a 3-meter class telescope in a 747SP, with no "show stoppers" having surfaced during development of the installation concept. The concept provides adequate load paths around the open port. The critical design load on the forward and aft bulkhead is pressurization, and for operating pressures the relative displacement between the bulkheads is less than 3 inches; the maximum rotation measured at the center of rotation is less than one-half degree. Preliminary analysis indicates that the combined structural members of this concept will maintain the fuselage bending stiffness and strength at approximately its original value with the large port. Further analysis is required to determine if this installation is sensitive from the standpoint of torsional strength, rigidity and dynamics (vibration and flutter modes).
2. A preliminary drag analysis was performed that estimated the potential performance impact in terms of equivalent flat plate area for the baselined configuration. Based on the performance data developed, the potential endurance at or above FL 410 (with door and fence tracking the telescope) is approximately 5.5 hours for a ramp weight of approximately 485,000 lbs.
3. For the concept developed, payload weights greater than 45,500 lbs (31,165 lbs forward payload and 14,335 lbs. aft) will require ballast to satisfy aircraft c.g. requirements. For the current payload goal of 61,875 lbs the ballast requirements are 10,020 lbs for a total payload of 71,805 lbs.
4. The design drivers analyzed during the study were selected on the basis of significant cost sensitive issues, and the effects of small (10 percent) changes in the telescope/mission requirements were evaluated. Based on this analysis the baseline aero-optic configuration (aft ramp and KAO-type fence) is a major performance/cost driver and should be studied further.

### **CONCLUSIONS**

- BOEING 747SP REMAINS AIRCRAFT OF CHOICE
- INSTALLATION CONCEPT APPEARS FEASIBLE
- DRAG ANALYZED AND AIRCRAFT PERFORMANCE ESTIMATED
- PAYLOAD/BALLAST RELATIONSHIP DEVELOPED
- MAIN DESIGN DRIVER IS POROUS FENCE - COST AND PERFORMANCE

## Issues and Recommendations

Three categories of issues/recommendations are presented from the aircraft system perspective. First are programmatic issues that should be addressed from a joint NASA/aircraft contractor (BMAC)/telescope contractor total integration/system performance standpoint. Resolution of the four integration issues can improve overall system performance and favorably impact program cost. These issues are the telescope size (where 3 meters has no volume/mass margin), telescope cavity environmental control (possible use of aircraft airconditioning system to reduce carryon weight/complexity), the aero-optics interface (porous fence drag), and the need for development of a program interface control document (ICD). Joint resolution of the first three issues will improve further development of the telescope and aircraft modification concepts, and provide meaningful critical inputs to a preliminary ICD.

The second category, configuration concept, addresses: structural/dynamic issues which require further development and analysis before initiating detail design (e.g., NASTRAN modeling); detail concept development (porous fence and door optimization, frame and stringer detail in cavity section, bulkhead/floor to monocoque interfaces, cavity design details, and doublers and sill beams required around open port); and the issue of allowable bulkhead deflection, which impacts modification weight.

The final category, aircraft system revisions, includes those systems concepts whose potential revision or improvement may have cost and performance impacts. These include: control cables, where rerouting of all cables as a result of the cavity location should be examined in further detail; environmental control system, where revisions appear straightforward but need further assessment, especially if the system is to be used for cavity conditioning; electrical/avionics systems, where a detailed analysis of changes required for SOPFA implementation (e.g., structural changes, power provisions, data system links) needs to be accomplished to identify conflicts and their resolution; and, an ultimate decision, after the system weight and drag values become settled, on the need for "enhanced" or even upgraded engines to achieve required mission performance.

### **ISSUES AND RECOMMENDATIONS**

- PROGRAMMATIC
  - TELESCOPE SIZE
  - CAVITY ENVIRONMENTAL CONTROL
  - AERO-OPTICS INTERFACE
  - INTERFACE CONTROL DOCUMENT
- CONFIGURATION CONCEPT
  - STRUCTURAL/DYNAMIC UNCERTAINTIES
  - DETAILED CONCEPT DEVELOPMENTS
  - BULKHEAD WEIGHT VS DEFLECTION REQUIREMENTS
- AIRCRAFT SYSTEMS REVISIONS
  - CONTROL CABLES
  - ENVIRONMENTAL CONTROL SYSTEMS
  - ELECTRICAL/AVIONIC SYSTEMS
  - ENHANCED/UPGRADED POWER PLANTS







## **SECTION 6**

### **INTEGRATION AND TEST**

- 6.1**      **Scope**
- 6.2**      **Integration Program Description**
- 6.3**      **Test Program Description**
- 6.4**      **Summary and Conclusions**

## Integration and Test Program

### Scope

A critical effort required for the successful accomplishment of any complex hardware development program is the planning, preparation, and performance of system integration and testing (I&T), flowing from the lowest component level through build-up stages to the system (observatory) level. Although technical feasibility is not an issue for the SOFIA I&T program, it is important in this early phase to define the scope, levels and general tasks required, in order to assign responsibilities amongst the various program elements and to provide a basis for cost estimating.

The major elements involved in the SOFIA I&T program are shown; it is envisioned that each element, which will likely involve a separate development effort (i.e., different contractors), will integrate and test that entire element as a distinct entity prior to system level I&T. A candidate flow for the entire program is shown later. Note here that the science instruments are not shown; in this regard an aircraft observatory program is quite different from a space program, in that many experiments will be routinely installed and removed from the SOFIA facility during its lifetime. Thus it is incumbent on the investigator team to integrate and test their experiment at their own facility; the SOFIA project will provide the necessary interface documentation (e.g., User's Guide), and facility simulator hardware/software at ARC to enable integration and checkout of the experiment with the facility. (Access to the facility simulator shall be provided early enough to assure successful integration prior to start of the experimenter's flight series.)

The test program must address not only the types of testing required, but the hardware "levels" at which they are performed. It is too early in the SOFIA program to define what is meant by component, unit, etc. for each program element, and this will have to be addressed in future phases. However, in general it is necessary to perform both environmental and functional tests on hardware elements as they are built up into subsystems, and then functional interface tests between subsystems and major elements at the observatory level.

### **SOFIA INTEGRATION AND TEST PROGRAM SCOPE**

- INTEGRATION PROGRAM - MAJOR ELEMENTS
  - TELESCOPE ASSEMBLY
  - CONSOLES AND ELECTRONICS SUBSYSTEM
  - AIRCRAFT SYSTEM
  - GROUND SUPPORT SYSTEM
- TEST PROGRAM
  - LEVELS
    - COMPONENT
    - UNIT
    - ASSEMBLY
    - SUBSYSTEM
    - SYSTEM (OBSERVATORY)
  - TASKS
    - ENVIRONMENTAL
    - ACCEPTANCE
    - QUALIFICATION
    - FUNCTIONAL

## Integration Program Description

### Preparation

The chart lists the major documentation and associated tasks needed for a successful system integration program. It is vital that a formal documentation process be undertaken to assure hardware compatibility and efficient integration amongst the major program elements. The most critical documents needed to assure successful integration are the interface control documents and drawings, which must address all the applicable technical disciplines, including structural/mechanical, thermal, electrical, command and data, etc. An interface control process is required at the project management level to maintain formal configuration control of all the elements; this process initially establishes baseline interface requirements and controls subsequent changes to assure continued compatibility across element boundaries. To enable successful configuration control, representatives must be appointed from all project elements to participate in a configuration control board, under the direction of central project management. The specifics of this process and organization will be developed as hardware responsibilities are clarified in future program phases.

Important ancillary functions of project management, which are needed to assure a successful development effort, include: continuing quality assurance, which is a separate "hardware verification" organization under each program element; regular integrated technical reviews of development progress and problems; cost and schedule planning and tracking; and ongoing evaluation/planning for spare hardware.

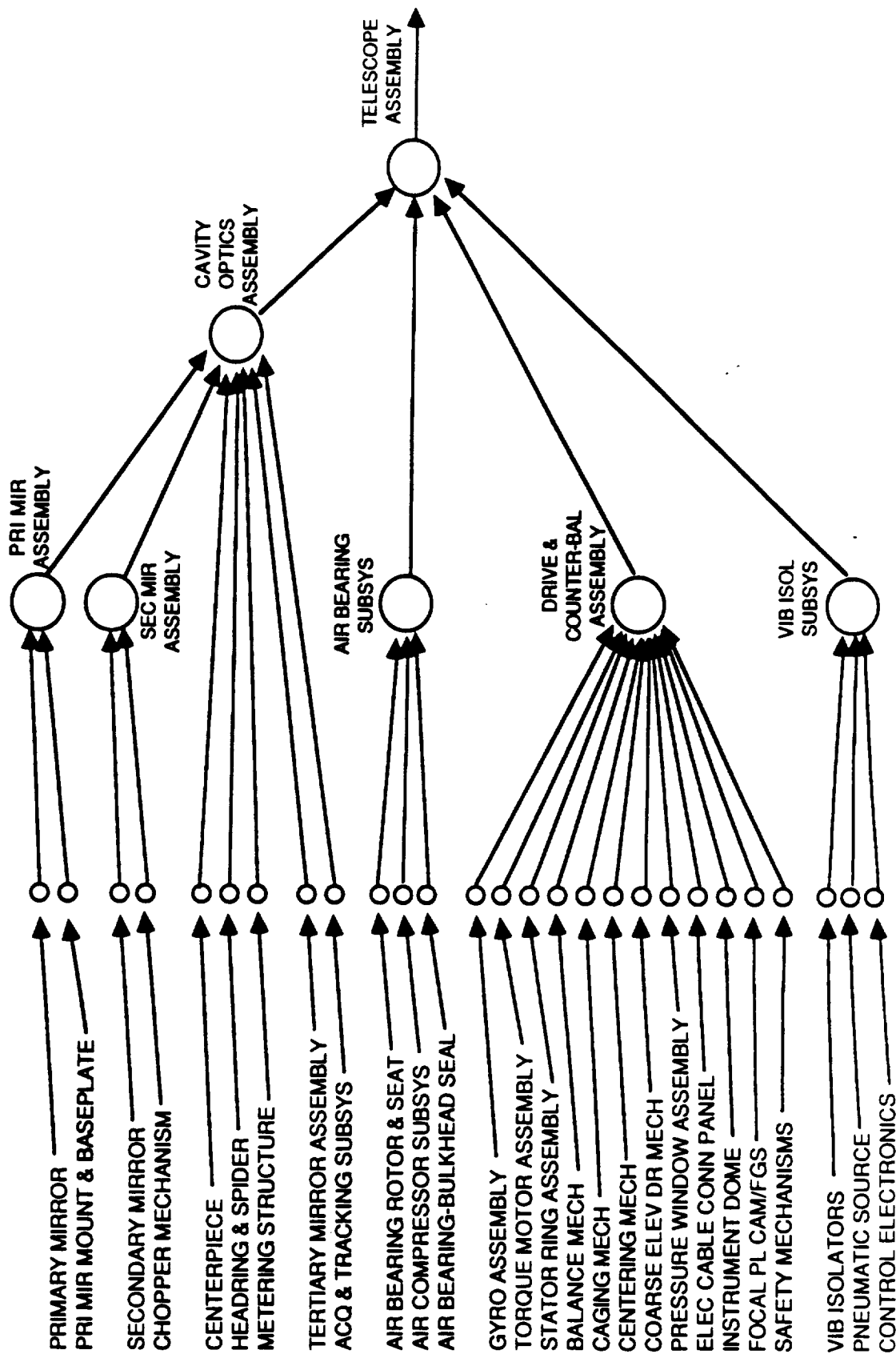
## **SOFIA INTEGRATION PROGRAM PREPARATION**

- DOCUMENTATION
  - SUBSYSTEM SPECIFICATIONS
  - DRAWINGS: SYSTEM DESIGN/FABRICATION/INSTALLATION
  - DESIGN REPORTS/SYSTEM DESCRIPTIONS/TECHNICAL ANALYSES
  - INTERFACE CONTROL DRAWINGS/DOCUMENTS
  - TEST PLANS AND PROCEDURES
  - OPERATION MANUALS
- ASSOCIATED TASKS
  - CONFIGURATION CONTROL
  - SAFETY, RELIABILITY, AND QUALITY ASSURANCE
  - TECHNICAL REVIEWS
  - SCHEDULE PLANNING AND MAINTENANCE
  - SPARES PROGRAM

#### **Telescope Assembly Integration and Test Flow**

The chart depicts a preliminary concept for the build-up of the telescope Assembly from its units, subsystems and sub-assemblies. It is envisioned that initial functional/environmental testing (as necessary) would take place at the unit levels shown on the left hand side, before subsequent integration to the next level. Further functional testing would take place at the second level(s), before final integration of the Telescope Assembly.

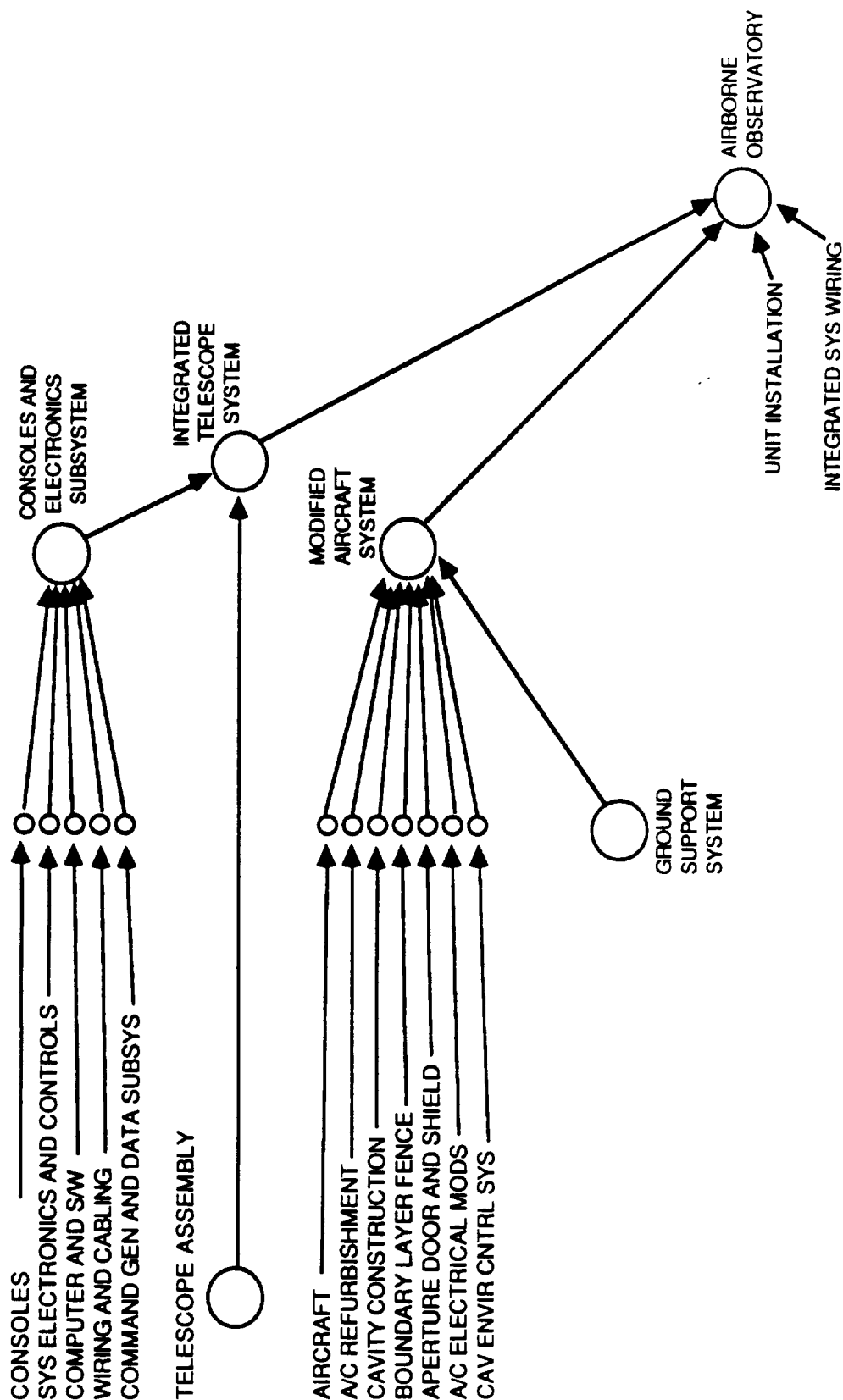
## INTEGRATION AND TEST FLOW DIAGRAM TELESCOPE ASSEMBLY



### Observatory Level Integration and Test

This chart continues the integration process depicted previously for the Telescope Assembly, combining the latter with the Consoles and Electronics Subsystem build-up, the Ground Support System and the modified Aircraft System development, culminating in a final integration at the Observatory level. Preliminary program schedules for these activities have been established, with a view toward concurrent delivery of the integrated Telescope System and the modified Aircraft System, for program efficiency. Subsequent to Observatory level integration, system functional (ground) tests and final flight tests will take place prior to dedication of the facility for initial science operations.

### INTEGRATION AND TEST FLOW DIAGRAM TO OBSERVATORY LEVEL



Test Program Description

The test program for the SOFIA major elements will be performed in various phases. For the aircraft modification element, early (Phase B) wind tunnel testing is planned using a sub-scale mockup of the aircraft forward fuselage section with the cavity modification. These tests will investigate various shear layer control options (e.g., fence with aft ramp, aft ramp alone) to identify an acceptable approach which creates minimum drag. These tests will also characterize the dynamic and acoustic loads in the cavity, and wind loads on the telescope (using a simple telescope model), to assist in design of the cavity and telescope structures. Measurements will also be taken of overall forces/torques on the fuselage to assess stability and control margins. After the aircraft modification is complete, flight testing will be performed to verify aircraft performance, stability and control, and the cavity environment; it has not been determined as yet whether these flight tests will use Telescope System mass simulators or will await actual installation of the Telescope System.

The Integrated Telescope System elements will undergo functional and environmental testing at various levels during their build-up as previously discussed. Environmental testing concepts are presented later. The final telescope system level tests may be performed in a ground facility, or after aircraft installation; verification of the pointing control system will, of course, require testing during flight.

As previously noted, the functional/environmental testing of the experiments (science instrument and control electronics) is the responsibility of the investigator team at their home facility. Upon delivery of the experiment equipment to NASA-Ames prior to a flight series, the experiment will undergo interface compatibility and functional tests using an ARC-based Telescope System simulator. The latter will duplicate all Telescope System interfaces and functions, allowing complete checkout of the experiment prior to installation in the aircraft.

### **ENVIRONMENTAL ACCEPTANCE TESTS**

- TESTS
  - VIBRATION
  - SHOCK
  - ACOUSTICS
  - THERMAL
  - LOW PRESSURE
  - HUMIDITY
  - ELECTRICAL POWER
  - EM/EMC
- ENVIRONMENT LEVELS
  - ACCEPTANCE: 1.25 TIMES EXPECTED ENVIRONMENTS - AS APPLICABLE
  - QUALIFICATION (SELECTED COMPONENTS): 1.5 TIMES

### Environmental Testing Baseline Concepts

The SOFIA program test approach will be analogous to a "protoflight" approach used in space hardware programs; that is, testing will be performed on the actual flight hardware, avoiding the expense of a prototype development program. This includes Telescope System and aircraft modification hardware, at appropriate build-up levels. For acceptance testing, the dynamic test environments (shown in the chart) will be at levels that are 1.25 times the predicted flight amplitudes. Performance margins will be demonstrated on selected parameters, such as power supply voltages greater or less than the expected operating ranges. It is possible that selected items with critical functions, such as operating mechanisms, will be subjected to qualification-level tests; these tests will verify a 1.5 design margin for dynamic loads. Finally, spares and refurbished units will be screened for workmanship by testing to acceptance amplitudes and duration.

### **MAJOR SYSTEM FUNCTIONAL AND ENVIRONMENTAL TESTING**

- AIRCRAFT SYSTEM
  - WIND TUNNEL TESTS OF CAVITY MODIFICATION
    - SHEAR LAYER CONTROL CONCEPTS
    - ACOUSTIC AND WIND LOADS IN CAVITY WITH TELESCOPE MODEL
    - DRAG INCREMENT, STABILITY, AND CONTROL
  - FLIGHT TESTS (OBSERVATORY LEVEL) - VERIFICATION
  - AIRCRAFT PERFORMANCE
  - STABILITY AND CONTROL
  - CAVITY ENVIRONMENT/SHEAR LAYER/DYNAMIC LOADS
- TELESCOPE SYSTEM
  - COMPONENT/ASSEMBLY LEVEL FUNCTIONAL AND ENVIRONMENTAL
  - INTEGRATED SYSTEM FUNCTIONAL AND ENVIRONMENTAL
- SCIENCE INSTRUMENTS
  - FUNCTIONAL/ENVIRONMENTAL TESTS AT INVESTIGATOR FACILITY
  - TELESCOPE INTERFACE TESTING USING ARC TELESCOPE SYSTEM SIMULATOR(S)

**Summary and Conclusions**

This section, has provided a preliminary, top-level description of the integration and test program planned for SOFIA. More detailed planning will be needed in future program phases to minimize risks in this area. A necessary precursor to the development of detailed I&T plans will be the allocation of specific hardware responsibility for the various program elements, which include the modified Aircraft System, the Telescope System, and the Ground Support System. The chart lists some of the important considerations for managing a successful SOFIA I&T program. As can be seen, they all basically address the need for defining responsibilities in various areas; development of appropriate statements of work, interface specifications, etc., will follow the hardware responsibility decisions. These documents must thoroughly address the requirements for each element, maintaining consistency both within and between the elements.

### **INTEGRATION AND TESTING PROGRAM NEEDS**

- WELL-DEFINED STATEMENTS OF WORK FOR ALL ELEMENTS
- INTERFACE DEFINITION AND REQUIREMENTS
- PERFORMANCE RESPONSIBILITIES
- TESTING RESPONSIBILITIES
- CORRECTIVE ACTION RESPONSIBILITIES



## **SECTION 7**

### **GROUND SUPPORT SYSTEM**

- 7.1 Ground Support Facilities**
- 7.2 Aircraft Ground Support Equipment**

## Ground Support Facilities

### Scope

This project provides Investigator, telescope system, aircraft system, and aircraft ground support facilities for the Stratospheric Observatory for Infrared Astronomy (SOFIA). The SOFIA is a 3-meter class telescope mounted in a Boeing 747 aircraft planned as a national observatory to continue NASA's Airborne IR Astronomy Program into the 1990's as the successor to the Kuiper Airborne Observatory (KAO).

The proposed two storey building provides office, laboratory and shop facilities for approximately 40 full time employees plus facilities for three teams of visiting researchers at a time (8 - 10 persons per team). Laboratory facilities accommodate a telescope simulator, static test facility, ADAMS simulator, experimental equipment support, shop and storage areas. Office facilities include computational support, astronomical and engineering libraries, and sleeping facilities for 24-hour operation.

The proposed nose dock provides: a controlled and covered environment in which telescope maintenance and removal may be performed, and where the mirror coating equipment may be housed; crane and rigging equipment for telescope/primary mirror removal; and office and storage space for telescope and aircraft support services.

The proposed location, between ARC flight line buildings N248 and N259, is accessible from existing ramps and taxiways and has long been planned to include a building and hangar facility. The proposed use of this location for SOFIA thus fits in with the Center's Master Plan for land use.

### **GROUND SUPPORT FACILITIES SCOPE**

- 16,600 SQUARE FOOT, TWO STOREY OFFICE/LABORATORY BUILDING
  - OFFICE, LIBRARY, CONFERENCE ROOM AREAS
  - LABORATORIES: TELESCOPE AND DATA SYSTEMS SIMULATORS, STATIC TEST FACILITY
  - EXPERIMENTAL EQUIPMENT SUPPORT
  - SHOP AND STORAGE AREAS
- 6,600 SQUARE FOOT, HIGH BAY NOSE DOCK
  - CONTROLLED AND COVERED ENVIRONMENT
  - CRANE AND RIGGING EQUIPMENT
  - MIRROR COATING FACILITY
  - OFFICE AND STORAGE SPACE FOR GROUND SUPPORT PERSONNEL AND EQUIPMENT
- LOCATION: BETWEEN BUILDINGS N248 AND N259, ADJACENT TO THE AMES FLIGHT RAMP
  - CONSISTENT WITH CENTER LAND USE PLAN
  - ACCESSIBLE FROM EXISTING RAMPS AND TAXIWAYS

## **Justification**

The Boeing 747 aircraft proposed for use as the platform for SOFIA is both larger and heavier than any aircraft currently based at Ames Research Center, and existing ground support facilities are inadequate for providing the aircraft, telescope, and research investigator requirements of such a facility as SOFIA.

No alternative solutions for ground support facilities have been identified as acceptable within the Center. Options investigated included the existing KAO nose dock, modifying the KAO nose dock, using the existing flight hangar (N211), and constructing a new full hangar with office and laboratory space. The proposed solution, an office/laboratory building and a 747 nose dock, is the most cost effective solution while remaining within the Center's plan for land use.

Demand for office, laboratory and hangar facilities is driven by the master SOFIA schedule, which details telescope installation, checkout, ground and flight tests in 1991-92. Ground Support Facilities completion in 1990 is critical for support of these tests. Facility non-completion can impact the SOFIA operations schedule.

### **GROUND SUPPORT FACILITIES JUSTIFICATION**

- EXISTING GROUND SUPPORT FACILITIES INADEQUATE FOR BOEING 747
- EXISTING OFFICE/LABORATORY FACILITIES INADEQUATE FOR SOFIA OBSERVATORY SUPPORT
- NO ACCEPTABLE ALTERNATIVES IDENTIFIED WITHIN THE CENTER
- DEMAND DRIVEN BY MASTER SOFIA SCHEDULE:
  - EQUIPMENT INSTALLATION AND CALIBRATION IN EARLY 1991
  - GROUND SUPPORT TESTS IN LATE 1991
  - FLIGHT TESTS IN LATE 1992

## 7.2

### Aircraft Ground Support Equipment

The Boeing 747SP aircraft proposed for use as the platform for SOFIA is both larger and heavier than any aircraft currently based at Ames Research Center, and equipment for ground support and routine maintenance of the aircraft is required.

A tug with a minimum of 50,000 pounds draw bar pull and a tow bar are required. As the aircraft is considerably taller than those serviced at Ames, a Hi-Ranger truck (cherry picker), lifts to extend thirty feet high, and a stair truck are necessary. A full complement of jacks is required to raise the aircraft and swing the landing gear (8 jacks total), as well as a complement of maintenance stands (6 total). Engine and APU change kits and engine stands are also necessary. In addition, miscellaneous tools, kits, parts, and instruments are required for routine aircraft maintenance and servicing. It should be noted that the equipment listed is a short list of minimum equipment requirements.

The accompanying list applies to aircraft maintenance and servicing. Additional hoists, ramps, stairs, platforms and/or lifts are required for telescope servicing and researcher support as instruments are moved into and out of the aircraft. These needs are to be determined.

### **GROUND SUPPORT FACILITIES AIRCRAFT GROUND SUPPORT EQUIPMENT**

STAIR TRUCK

GENERATOR SET

TOWING TRACTOR/BARS

HI-RANGER TRUCK (CHERRY PICKER)

AIRCONDITIONER UNIT

ENGINE CHANGE KIT/STAND

APU CHANGE KIT

ENGINE STAND

AIRCRAFT JACKS (8)

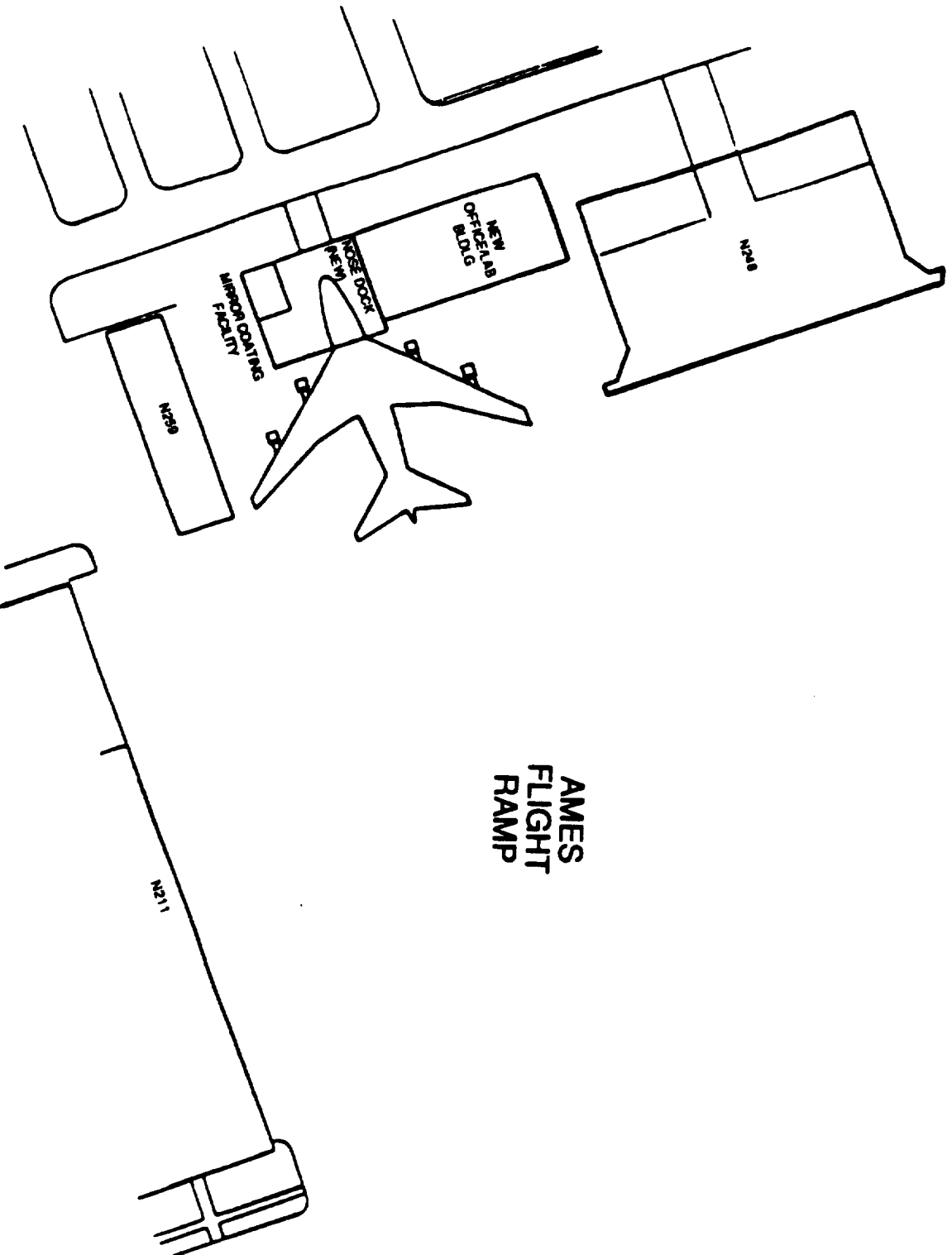
WORK STANDS

PORTABLE SCALES

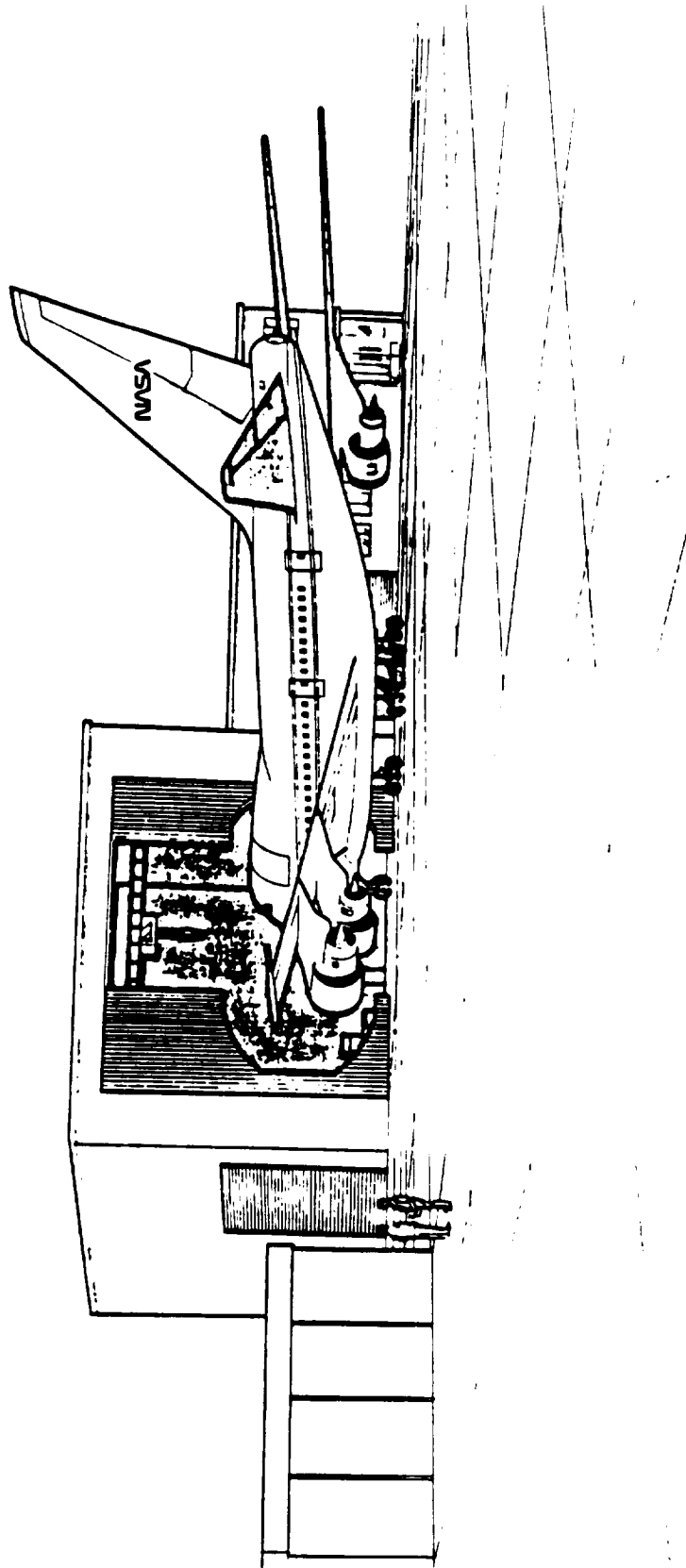
AIRSPEED TESTER

MISCELLANEOUS TOOLS, KITS

## GROUND SUPPORT FACILITY PROJECT LOCATION



### GROUND SUPPORT FACILITY NOSE DOCK









## **SECTION 8**

### **OPERATIONS SYSTEM**

- 8.1**      **Goals and General Plan for SOFIA Operations**
- 8.2**      **Project Management and Administration**
- 8.3**      **Investigator Selection**
- 8.4**      **Ground Operations**
- 8.5**      **Flight Operations**
- 8.6**      **Science Data Analysis**

## **8.1 GOALS AND GENERAL PLAN FOR SOFIA OPERATIONS**

- FLIGHT RATE: 120 RESEARCH FLIGHTS/YEAR
  - ULTIMATE GOAL
  - REQUIRES A MINIMUM OF 3 YEARS TO ACHIEVE
- INVESTIGATOR TEAMS: 25-30 TEAMS/YEAR
- WORK SCHEDULE:
  - 7 DAYS/WEEK
  - 3 SHIFTS/DAY
- TYPICAL FLIGHT SCHEDULE
  - RESEARCH FLIGHTS - MONDAY, WEDNESDAY, FRIDAY
  - CHANGE EXPERIMENTS, MAINTENANCE, ETC. - SATURDAY, SUNDAY
- STAFFING:
  - CIVIL SERVANT AND SUPPORT SERVICE CONTRACT

### **GOALS AND GENERAL PLAN FOR SOFIA OPERATIONS (CONTD)**

- YEARLY SCHEDULE
  - 40 WEEKS FOR RESEARCH FLIGHTS @ 3 FLIGHTS/WEEK
  - 12 WEEKS FOR SUPPORT ACTIVITY
    - 3 WEEKS - AIRCRAFT PERIODIC MAINTENANCE
    - 2 WEEKS - PILOT TRAINING AND PROFICIENCY
    - 4 WEEKS - MAJOR TELESCOPE MAINTENANCE AND MODIFICATIONS
    - 3 WEEKS - "MAKE-UP" DUE TO DIFFICULTY IN SCHEDULING MON/WED/FRI FLIGHT SERIES (HOLIDAYS, CONTINGENCIES, GROUNDINGS, ETC.)

## **8.2 PROJECT MANAGEMENT AND ADMINISTRATION**

### SOFIA PROJECT OFFICE - ARC

- OVERALL RESPONSIBILITY FOR ADMINISTRATION AND MANAGEMENT OF APPROVED PROGRAM

### OVERSIGHT

- HEADQUARTERS PROGRAM OFFICE(S)
- SOFIA USERS
- ANNUAL MEETING OF ALL USERS
- QUARTERLY MEETING OF USERS SUBGROUP, EQUIVALENT TO "MOWG" FOR AIRBORNE ASTRONOMY

### COORDINATION WITH OTHER AMES GROUPS

- E.G., AIRCRAFT OPERATIONS DIVISION TO DIRECT DAILY SUPPORT AND PARTICIPATION

### COORDINATION WITH SUPPORT SERVICE CONTRACTORS (SSC)

- SSCs UNDER SOFIA PROJECT OFFICE CONTROL, E.G.,
  - DATA SYSTEMS
  - ENGINEERING, TECHNICAL, AND LOGISTICS

### **PROJECT MANAGEMENT AND ADMINISTRATION (CONTD)**

#### **FISCAL MANAGEMENT**

- PREPARATION OF YEARLY BUDGETS FOR "POP CALLS"
- MONITORING AND CONTROL OF APPROVED BUDGET

#### **SCHEDULING**

- PREPARATION OF YEARLY FLIGHT SCHEDULE
  - UPDATE ON MONTHLY AND WEEKLY BASIS
- ELEMENTS OF YEARLY SCHEDULE
  - RESEARCH FLIGHTS
  - FACILITY ENGINEERING FLIGHTS
  - PILOT PROFICIENCY FLIGHTS
  - AIRCRAFT AND TELESCOPE MAINTENANCE PERIODS

## **PROJECT MANAGEMENT AND ADMINISTRATION (CONTD)**

### **DEPLOYMENT PLANNING**

- GENERAL ELEMENTS
  - SUPPORT FACILITIES AT DEPLOYMENT BASE:
    - AIRCRAFT SERVICES
    - SOFIA FACILITY SUPPORT
  - HOTEL AND TRANSPORTATION
  - TRANSIT FLIGHTS - RESEARCH OR FERRY
- TYPES OF DEPLOYMENTS
  - DOMESTIC - TO USA TERRITORY
  - INTERNATIONAL
    - CLEARANCES FROM HOST GOVERNMENTS
    - PASSPORTS AND VISAS

### 8.3 INVESTIGATOR SELECTION

- "ANNOUNCEMENT OF OPPORTUNITY" ISSUED ANNUALLY IN OCTOBER
  - "LETTER OF INTENT" DUE NOVEMBER 30
  - PROPOSAL DUE FEBRUARY 28
- PROCESSING OF PROPOSALS
  - INITIAL RECEIPT

#### AMES UNIVERSITY AFFAIRS OFFICE

#### HEADQUARTERS INTERNATIONAL AFFAIRS OFFICE

- CATALOGUING, REDISTRIBUTION

#### SOFIA PROJECT OFFICE

- EVALUATION AND RANKING OF PROPOSALS
- PEER REVIEW COMMITTEE MEETS IN SPRING
- COMPOSITION - ASTRONOMERS NOT PROPOSING FOR SOFIA FLIGHTS
- FUNCTIONS

#### REVIEW AND RANKING OF PROPOSALS

#### RECOMMENDATIONS TO HEADQUARTERS PROGRAM OFFICE

#### SCOPE OF SOFIA RESEARCH

#### ALLOTMENT OF FLIGHTS

## **INVESTIGATOR SELECTION (CONTD)**

- **APPROVED BY HEADQUARTERS PROGRAM OFFICES**
  - **PI SELECTION**
  - **ASSIGNMENT OF FLIGHTS**
  - **ALLOTMENT OF FUNDING TO PIs**
- **IMPLEMENTATION OF APPROVED PROGRAM**
  - **NOTIFICATION TO PIs - PROGRAM OR PROJECT SCIENTIST**
  - **SCHEDULING OF FLIGHTS - SOFIA PROJECT OFFICE**
  - **DISBURSEMENT OF PI FUNDING - SOFIA PROJECT OFFICE**
  - **MONITORING OF GRANTS AND DISBURSEMENTS - SOFIA PROJECT OFFICE**
  - **COORDINATION WITH PIs - SOFIA PROJECT OFFICE**

### **8.4**

#### **GROUND OPERATIONS**

##### INTERACTION WITH PI TEAMS

- DESIGNATION OF A "MISSION DIRECTOR" FOR EACH PI
- RESPONSIBLE FOR COORDINATING ALL SUPPORT OF A PIs FLIGHT SERIES
- TYPICAL SEQUENCE OF A PIs FLIGHT SERIES
- COORDINATION OF REQUIREMENTS FOR SUPPORT
- ARRIVAL OF TEAM
- INSTALLATION OF PIs INSTRUMENT(S)
- RESEARCH FLIGHTS
- REMOVAL OF PIs INSTRUMENT(S)

##### TELESCOPE SYSTEMS MAINTENANCE

- REPAIRS ASAP TO MAINTAIN FLIGHT SCHEDULE
- PREVENTIVE MAINTENANCE
- PLANNED SCHEDULE OF "INSPECTION AND REPAIR AS NEEDED" (IRAN)
  - SHORT-TERM ITEMS ( $\leq 2$  DAYS)
- NON-INTERFERENCE BASIS WITH WEEKLY SCHEDULE
- LONG-TERM ITEMS ( $\geq 3$  DAYS)

SCHEDULED GROUNDING OF AIRCRAFT FOR PERIODS OF 2 WEEKS - TWO TIMES A YEAR

## GROUND OPERATIONS (CONTD)

### AIRCRAFT MAINTENANCE

- REPAIRS ASAP TO MAINTAIN FLIGHT SCHEDULE
  - REQUIRED PERIODIC INSPECTIONS
    - MONTHLY - NON-INTERFERENCE BASIS WITH FLIGHT SCHEDULE
    - SEMI-ANNUAL, ANNUAL, BIENNIAL
    - SCHEDULED GROUNDING OF AIRCRAFT
- PROBABLY DONE AT A MAJOR AIRCRAFT MAINTENANCE BASE

### **8.5 FLIGHT OPERATIONS**

#### **FLIGHT PLANNING**

- PI INPUT TO NAVIGATORS (TARGET LIST)
  - PRELIMINARY -  $\leq 1$  MONTH PRIOR TO FLIGHT
  - INTERMEDIATE - BY THURSDAY OF WEEK PRECEDING FLIGHT
  - FINAL - DAY OF FLIGHT
- TAKE-OFF (T.O.) TIME POSTED BY 1200 ON DAY OF FLIGHT

#### **PREFLIGHT ACTIVITIES - DAY OF FLIGHT**

- AIRCRAFT
  - FUELING AND PREFLIGHT CHECK OF SYSTEMS - EARLY AM
- TELESCOPE
  - PREFLIGHT CHECK OF SYSTEMS - AFTERNOON
  - PRE-COOL ~ T.O. - 4 HRS
- PASSENGER CHECK AT 1300 STAFF MEETING
  - SAFETY PROCEDURES, OXYGEN MASK CHECKS

## FLIGHT OPERATIONS (CONTD)

### IN-FLIGHT ACTIVITIES

#### • FLIGHT TIMELINE

T.O. - 60 M	PREFLIGHT BRIEFING; MANDATORY FOR ALL PARTICIPANTS
T.O. - 45 M	BOARD AIRCRAFT
T.O. - 25 M	DOOR CLOSES
T.O. - 15 M	START TAXI
T.O. - 0	AIRCRAFT LIFTS OFF RUNWAY
T.O. + ~30 M	AIRCRAFT AT FIRST CRUISE ALTITUDE OPEN DOOR; START OBSERVATIONS
T.O. + ~7 H	END OBSERVATIONS; CLOSE DOOR, START CAVITY PURGE, START DESCENT
T.O. + 7H30M	LAND
	SECURE AIRCRAFT AND TELESCOPE SYSTEMS (~30 MINUTES)

### **FLIGHT OPERATIONS (CONTD)**

#### **FLIGHT PARTICIPANTS**

- FLIGHT CREW (3)
- SOFIA STAFF (3-4)
- PI TEAM (3-8)

#### **AUTHORITY DURING FLIGHT**

- MISSION MANAGER
  - DIRECTS ALL OPERATIONS FOR FULFILLMENT OF MISSION OBJECTIVES AND TELESCOPE PERFORMANCE
- CHIEF PILOT
  - AUTHORITY IN ALL ASPECTS OF AIRCRAFT OPERATION AND SAFETY

#### **ROLES DURING FLIGHT**

- FLIGHT CREW
  - PERFORMANCE OF AIRCRAFT
- SOFIA TELESCOPE AND SUPPORT CREW
  - OPERATION OF TELESCOPE AND SOFIA PROVIDED DATA SYSTEMS
- PI TEAM
  - RESPONSIBLE FOR PROVIDING AND OPERATING THE DETECTING INSTRUMENT AND CONTROL SYSTEM

## 8.6 SCIENCE DATA ANALYSIS

### DATA COLLECTION DURING FLIGHT

- RESPONSIBILITY OF PI
- METHOD OF COLLECTION
  - EITHER SOFIA DATA SYSTEM
  - OR PI-SUPPLIED DATA SYSTEM

### DATA ANALYSIS

- RESPONSIBILITY OF PI
- "QUICK-LOOK" ANALYSIS DURING FLIGHT
- DEFINITIVE ANALYSIS BY PI AT HOME BASE

### **SCIENCE DATA ANALYSIS (CONTD)**

#### **DATA REPORTING AND PUBLICATION**

- PRESENTATIONS AT MEETINGS AND CONFERENCES
- PREPRINT SERIES OF THE AIRBORNE ASTRONOMY PROGRAM
- PUBLICATION IN PROFESSIONAL JOURNAL
- REPRINTS TO SOFIA PROJECT OFFICE
- LISTING IN BIBLIOGRAPHY OF AIRBORNE ASTRONOMY PROGRAM

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